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[*Continued on page (III) of Cover.*

# FIRE PRECAUTIONS IN MAJOR ELECTRICAL STATIONS

By F. C. WINFIELD, M.Eng., Member.

(*Paper first received* 6*th October and in revised form* 25*th November*, 1936; *read before* THE INSTITUTION 11*th February, before the* NORTH-EASTERN CENTRE 8*th February, before the* NORTH MIDLAND CENTRE 16*th February, before the* NORTH-WESTERN CENTRE 2*nd March, before the* SOUTH MIDLAND CENTRE 8*th March, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 15*th March, and before the* TEES-SIDE SUB-CENTRE 16*th March*, 1937.)

## SUMMARY

The paper discusses precautions to be adopted in respect of fire in power stations and major system substations arising from failures of electrical plant.

General considerations are discussed first, and it is pointed out that whilst electrical duplication or multiplication of plant is recognized as essential, its complement—true physical segregation of duplicates to secure against the fire or explosion risk—has not received as much attention.

It is, however, emphasized that the rare occurrence of serious fires or explosion justifies a different treatment and that it suffices in general to segregate duplicates in two separate groups. The condition of rarity is secured only by the use of sound plant and good protective gear, and it is essential that this condition should be maintained and desirable that it should be improved upon.

It is emphasized, nevertheless, that despite all precautions fire cannot be absolutely precluded and that the only ultimate safeguard must be a reasonable fire-sectioning of the plant, so that a fire or explosion is limited in its worst effect to a section or group of plant items which can in emergency be done without.

Given these two conditions, the prime requirements are met. The second stage is the limitation of the consequential damage following a fire to a degree which will ensure that the subsequent emergency state shall not continue too long, as during this period the essential principle of electrical duplication no longer holds and electrical faults are relatively frequent.

This leads to the discussion of additional precautions which can be taken to decrease the consequential damage by improvements in design within the agreed fire sections, and by fire-fighting arrangements.

General details are discussed and examples given, and the explosion risk is referred to.

## INTRODUCTION

Serious fires from electrical plant in power stations or major substations in this country are fortunately very rare, but in the last few years several disastrous fires both at home and abroad have reminded supply engineers that the risk does exist and that the consequences of inadequate provision for meeting it may be of the gravest nature.

In electrical supply engineering the maintenance of supply is accepted as an overriding requirement, and in its purely electrical reactions this condition is usually met by the duplication or multiplication of all principal feeders and items of plant. Since all electrical plant is subject in some degree to the twin risks of fire or explosion, however, this simple provision does not secure the desired assurance of maintenance of supply unless it is supported by measures to ensure that such duplicates cannot be simultaneously impaired by fires or explosions resulting from electrical failures, which means that it is necessary to provide physical separation or sectioning of electrical duplicates by dividing them up in a suitable degree in separate buildings or enclosures.

To a lesser but still important extent it is desirable to add provision for restricting the extent of the general damage consequent on any single failure.

In considering this aspect an important difference in degree may be noted between the considerations affecting electrical duplication and those applying to physical duplication or segregation. (For convenience in terminology the term " duplication " will be assumed throughout to cover both simple duplication and its alternative—multiple subdivision.) This difference in degree arises from the relative frequency of the troubles or failures to be guarded against.

The non-availability of some single item of electrical equipment because of failure, maintenance, testing, or other reasons, is a relatively frequent occurrence, and this frequency makes imperative the provision of complete or nearly complete duplication of each item of plant. The incidence of serious fire, however, is of an entirely different and lower order of frequency, and because of this the risk from this source is reasonably susceptible of less detail treatment. It is important to fix this point of view. It is our duty as engineers to give the maximum public service at the lowest cost. Service includes such factors as reliability of supply. Technical perfection is neither possible nor economically practicable, and it is our duty to seek the best compromise between absolute reliability and lowest cost, as we must supply electricity at rates which permit its full use by the community.

Clearly one could carry precautions to an illimitable extent, but that is not engineering nor public service. Such an outlook would sweep every motor-car from the roads and every train, steamship, or aeroplane from human service, whilst totally failing to achieve its object. Our solutions must be practical and must balance precautions against risk, and we must not be stampeded by single exceptional occurrences. Serious fire is a rare occurrence in major electrical engineering. It is probably reasonable to describe it as a 100-year emergency. If the fire trouble were a frequent or even annual occurrence it would be necessary to adopt a very different outlook from that which experience justifies. A temporary interruption of, say, half an hour or even an hour or more's duration is quite permissible in the circumstances. An interruption occupying several days, however, is not permissible, as the disturbance to our modern social organism would be of too serious an order.

The main objective of the designer is to ensure that an exceptional occurrence, like a fire, does not seriously affect the public supply of electric power. In practice

this means a reasonable fire-sectioning of the plant so that in its worst effect a fire or explosion is limited to a section or group of plant items which in emergency can be done without. In what follows such a group is referred to as a "fire section."

Before considering this principle in more detail it may be noted that experience does not indicate that the risk of firing adjacent buildings or of direct injury to the outside public is a serious factor. This risk must exist in some degree, but the author is unable to recall any instance in the last dozen years in which a fire in a major substation or power station has produced material consequential damage to adjoining property or injury to persons.

Lastly, owing to the rarity of serious fires in power stations or major substations, the actual loss sustained in damaged equipment or buildings is not of importance.

## PRINCIPLES GOVERNING REDUCTION OF FIRE RISK

The chief points in the argument so far developed may be briefly summarized as indicating that the prime requirement in taking precautions against fire or explosion is that "the eggs shall not be carried in one basket." On the other hand, the conditions do not require that this principle shall be carried so far that each "egg" is in a separate basket. A single clear division of plant into two parts is frequently sufficient.

The governing principles in fire considerations may be enumerated in three classes:—

(*a*) *Provision which ought always to be made.*—(1) The use of switchgear and plant of adequate capacity, soundly designed and constructed, and provided with suitable automatic protective arrangements. (2) The complete electrical and fire sectioning into at least two duplicate parts of the switchgear, transformers, cables, etc., supplying an electric system or independent portion of a system. (3) Minimum arrangements for fire fighting. (4) Heating of buildings, to reduce risks of insulation failures.

(*b*) *Provisions which are easy and inexpensive to make and which reduce the spread of fire or consequential damage within a fire section.*—(1) Sealing of holes in floors or internal parts of any single fire section which has natural structural barriers. (2) The elimination of combustible matter not inherent to plant, e.g. waterproofing of cables, oil stores, etc.

(*c*) *Provisions which whilst not essential are desirable and should be applied where the importance or special conditions of the station justify the expenditure.*—(1) Floor drainage to remove oil quickly. (2) Permanent and local fire-extinguishing plant, either automatic or remote-controlled if the station is permanently attended.

These points may now be considered in detail.

## CHOICE OF PLANT

It has already been indicated that a serious fire is a rare occurrence. It is desirable that this condition should be maintained, which means that it is essential that sound plant and equipment should be employed. Further, rapid isolation of a fault is an important factor in reducing the risk of development of fire, and hence sound quick-acting protection is necessary.

The mere provision of sound plant is not in itself sufficient. No human construction is absolutely reliable. For example, no matter how well a circuit breaker is constructed a breakdown may be produced by an error in operation or maintenance, a hidden mechanical weakness, the failure of a crane or other tool, or the failure of the weakest part of all, the insulation. For this reason there can be only one practical ultimate guarantee against total and long-time interruption of supplies—a sound physical division between duplicate sections or groups of plant. Sound physical layout is even more important than sound plant.

## FIRE-SECTIONING

The sectioning of plant into two parts is a matter which, although simple in principle, seems in the author's experience to be rarely appreciated properly in its detail application, possibly because inadequate consideration is given to the problem.

For convenience the problem will be discussed first in respect to indoor metalclad switchgear, and the remarks will then be qualified in their relation to other types of switchgear and plant.

The diagrams in Fig. 1 illustrate the application of the simple principles of sectioning to switchgear, and are generally indicative of the problem as applied to plant of other types, although many variations of these simple types are possible.

The use of the term "duplicate busbar" is avoided in this paper unless certain conditions are fulfilled; "double busbar" is preferred. Busbars are not true duplicates in the fire-risk sense unless each busbar with its associated busbar isolators is mounted in a fireproof chamber separate from the other busbar and isolators and from the circuit breakers. If duplicate circuit breakers are employed for each feeder (an arrangement which in the opinion and experience of the author is unnecessarily expensive, since the duplicate feeder already carries a duplicate circuit breaker) each separate busbar should be associated with its corresponding circuit breakers in a fireproof chamber. Further, irrespective of whether one or two circuit breakers are employed per feeder, since the feeder itself is necessarily singular, in a true duplicate scheme the feeder terminals with the feeder isolators must be mounted in separate fireproof enclosures. The section circuit-breaker must also occupy a separate chamber. In practice this kind of arrangement can be secured as shown in Fig. 1(*g*), but applies particularly to open-type switchgear both outdoor and indoor, and requires large site-area or buildings.

This point is given special note as it brings out a natural difference in the treatment of the more usual forms of metalclad switchgear and of open-type switchgear. Open-type switchgear, being effectively an assembly of separate parts on site, has a greater flexibility which readily permits of a treatment such as that shown in Fig. 1(*g*), whereas with metalclad switchgear the essential fire conditions can more readily be met by arrangements such as that of Fig. 1(*f*). Broadly, the author regards Fig. 1(*g*) as representative of true duplicate busbars in the fire-sectioning sense, whereas Fig. 1(*f*) is representative of true duplicate busbar sections. Both forms, of course, give normal duplicate-busbar facilities in the purely electrical sense.

## Cables and Accessories

Whilst the diagrammatic representation of Fig. 1 shows switchgear only, it must be borne in mind that associated with each switch are main and control cables, relay panels, batteries, and other accessories, and it is necessary to stress that fire-sectioning must be complete and must include associated and auxiliary parts as well as main items of plant.

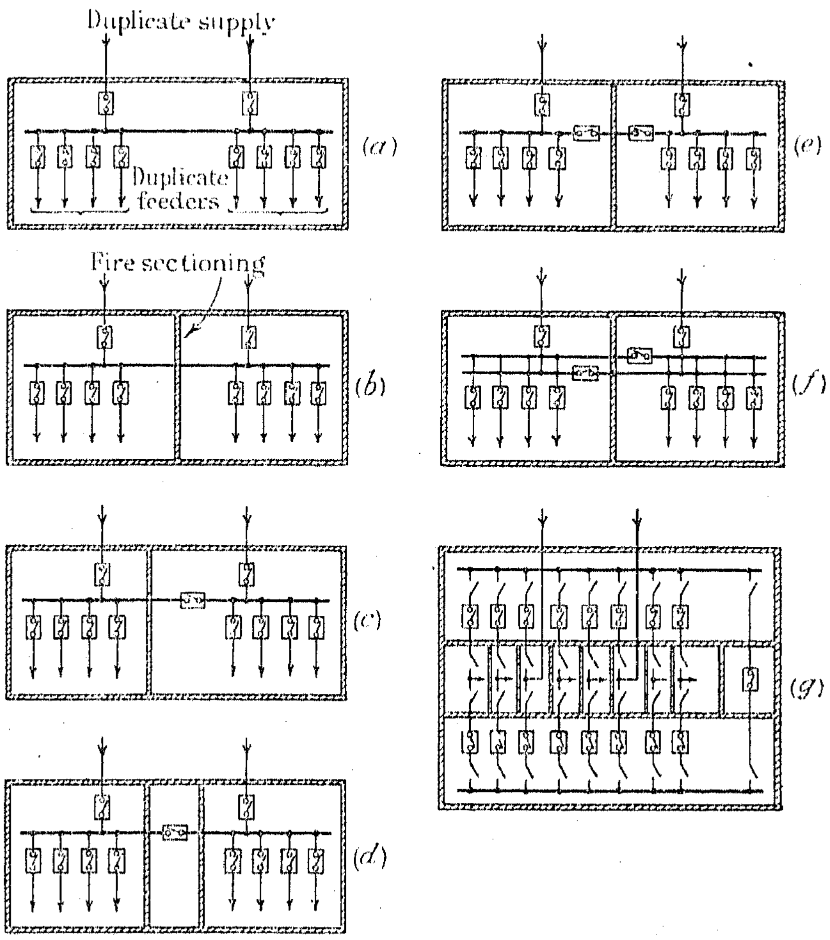


**Fig. 1.**—Typical diagrammatic arrangements of switchgear, showing fire-sectioning.

For clarity, no isolators are shown in these diagrams except where these are required for a fire isolation [see diagram (*g*)]. The fire-sectioning barriers shown are intended to indicate the segregation of duplicate groups of feeders, etc., into separate fireproof enclosures, not essentially fireproof in themselves but fireproof each against failure of the other. Duplicate feeders, generators, or transformers, must be distributed as equally as possible between the two sections.

(*a*) A very common arrangement. No sectioning. "Eggs all in one basket." Complete loss of switchboard possible. Should rarely be employed, and only for low-voltage low-capacity work.
(*b*) Nearly all objections to (*a*) apply also to this arrangement. Is better than (*a*) only because it may prevent complete loss of switchboard and reduce total damage.
(*c*) Fault-sectioning may be no better than in (*b*) for fire in right-hand chamber.
(*d*) Slightly incomplete, as section switch may fail, involving both busbar sections. Has given good results in practice and is suited to medium-power work.
(*e*) True sectioning.
(*f*) True sectioning in double-busbar application.
(*g*) Duplicate busbars with duplicate circuit breakers per circuit. Circuit cable and circuit isolators must be segregated from remainder, for true sectioning.

The author strongly favours, on general engineering grounds, what may be called the "unit principle" in electrical arrangements. This may be defined as the provision of each major item of equipment with its own separate and distinct control and auxiliary equipment, e.g. separate control cable, control panel, relays, etc. This arrangement has the further advantage that it facilitates fire segregation. It is not practical engineering to carry such unitization to the limit, as certain items of control—e.g. batteries, control panels, etc.—must, for economical reasons, be common or have common parts. It suffices that such unitization can be made practically complete within the principal fire enclosures, i.e. the main fire-risk points, and the common apparatus can be mounted in a separate fire enclosure, usually one in which the fire risk can be kept very low.

If it now be assumed that a sectioning of switchgear has been adopted on lines similar to those of Fig. 1(*e*), 1(*f*), or 1(*g*), it is necessary to ensure that this sectioning embraces the associated main and control cables, etc. This implies only that the main and control cables associated with the group of switch panels inside one fire section shall not pass into the duplicate fire section but must be self-contained or pass separately to the control centre, where such exists separately.

It is worth emphasis here that so long as each of the duplicate groups of switchgear, together with its main and control cables, control panels, etc., is enclosed in a separate fire section the prime principle of fire-sectioning is fulfilled, and nothing further is essential.

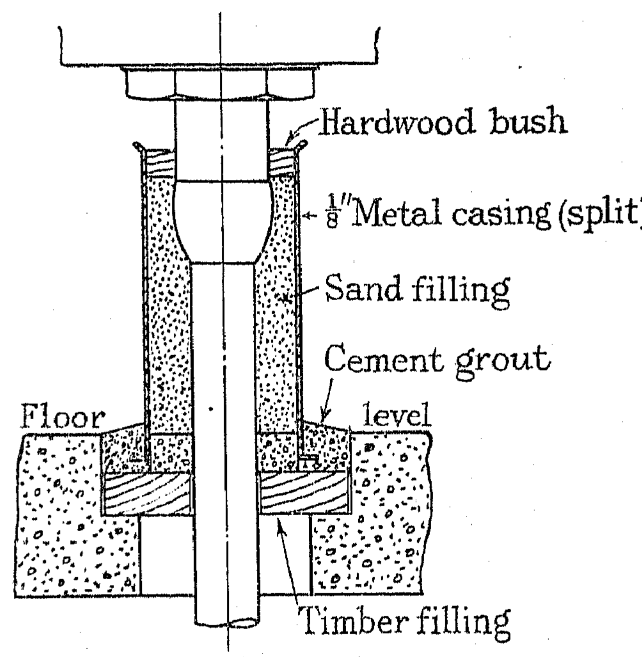


**Fig. 2.**—Arrangement for fire protection of cables connected to switchgear.

In practice, however, if the restoration of completely normal conditions following the loss of this fire group is not to be delayed for many months, something more than this is usually desirable and, fortunately, is usually achieved in large part through quite separate considerations. Thus, control panels, batteries, etc., usually are mounted in distinct chambers, whilst separate cable chambers frequently occur naturally.

The direct necessity remains for sectioning such cable chambers in the same way as the main switchgear, but it is also possible at small cost to go further and reduce the amount of consequential damage following a fire in the main switch chamber, or vice versa, by forming a complete fire division between switch and cable chambers by the sealing of holes in floors, cable exits, etc. A suggested method of sealing cables through floors is shown in Fig. 2. Where single cables leave a chamber horizontally through walls these may be sealed by light mortaring or plastering, and where groups of cables leave a chamber in trenches a simple method of sealing is to fill the trench or portion of it with sand or gravel.

Where true cable chambers exist, oil-filled electrical

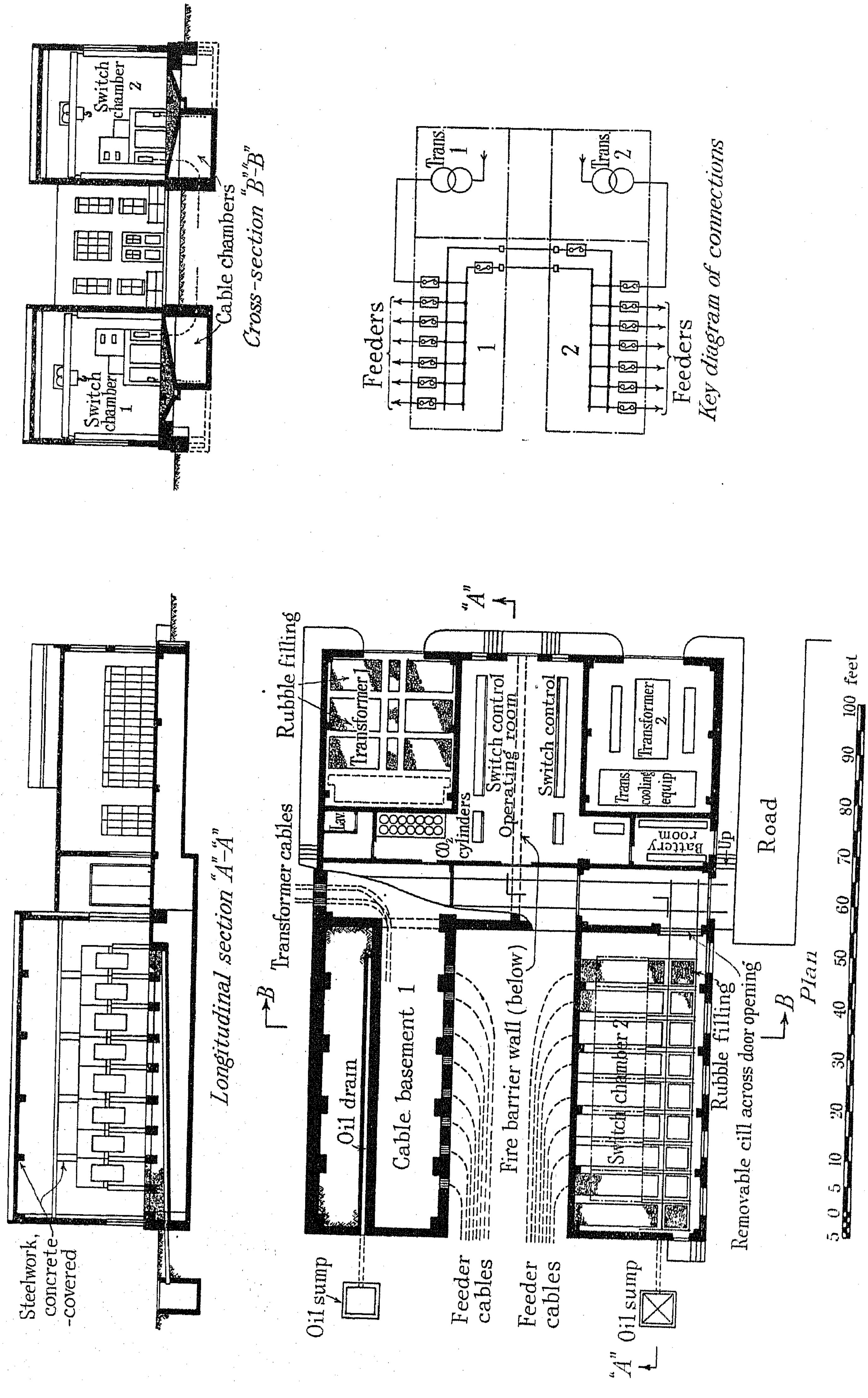


**Fig. 3.**—Typical arrangement of 33-kV substation using metalclad switchgear.

apparatus or bare live conductors in such chambers should be avoided, as also should all non-essential inflammable material such as cable waterproofing or stores. The initiation of a serious fire in a reasonably arranged cable chamber is unknown in the author's experience. Fires in cable chambers usually start elsewhere and are communicated through imperfect sealing.

It is sometimes suggested that control cables ought to be segregated from power cables. Provided no control cables common to several fire sections are in question the author cannot agree that there is any prime principle requiring this. It is, however, desirable, where busbar protection does not exist, to arrange that in any fire in a switch chamber the fire risk to the portions of control cables within the chamber is reduced sufficiently to ensure a reasonable period after the initiation of the fire during which tripping control remains available. In practice, lead-covered cables give this security to a degree, but this can be supplemented by light metal enclosure.

It is further suggested that individual power cables ought to be individually fire-protected. Again, in the author's view, principle and experience do not justify any material expenditure in this manner.

## Operating Rooms

In operating rooms it is usually inconvenient and unsatisfactory to introduce fire segregation in chambers. in a properly laid-out operating room the risk of serious fire is small, as only low voltages and low power are employed. There are, however, certain precautions which ought to be taken. The use of cubicle-type control panels, or at least some division of control panels in groups by steel or concrete barriers, is desirable, as is the enclosure of control switches subject to arcing at the contacts and the use of fire-resisting control wiring. Fire-resisting control wiring of very high standard is now obtainable, but investigation of still better forms is desirable. It is also frequently possible and convenient to enclose panel wiring in large part in metal ductways. Where control-cable basements occur beneath operating rooms it is usually possible to section these without difficulty.

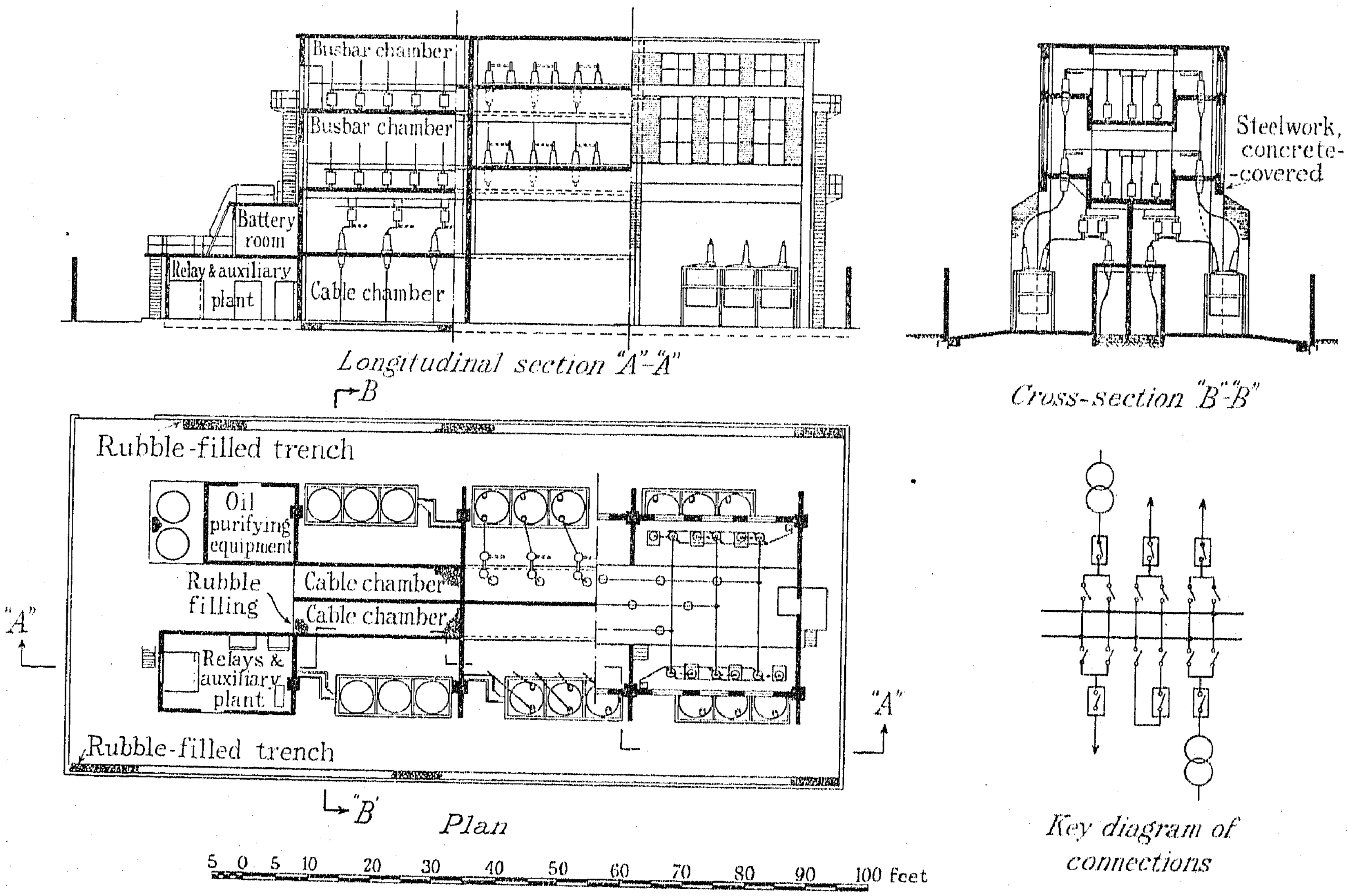


**Fig. 4.**—Typical arrangement of 66-kV substation using indoor open-type switchgear.

It is undesirable that direct communicating doors should be arranged between operating rooms and switchgear chambers, as the heavy smoke associated with fires may cause serious interference with operation at a time when it is least wanted. Similarly it is considered preferable in general to separate operating rooms in power stations from turbine rooms, etc., so that fire or other disturbance in the latter may not inconvenience or agitate the switchboard operators.

## Metalclad Switchgear

The foregoing remarks have borne particular consideration to metalclad indoor switchgear arrangements, and it is worthy of note that in the author's direct experience the fire-resisting capacity possessed by this

type of switchgear is extraordinarily high. In several fires of which he has knowledge and which have raged for hours, only the faulty panel has been seriously affected, the adjacent ones slightly, and the remaining panels in the same chamber have required little more than a thorough cleaning. An exception to this statement may arise in connection with the use of aluminium. This is a cheap and convenient metal to use where enclosure of heavy current-carrying parts is necessary. Unfortunately, in any severe fire, directly-exposed aluminium chambers invariably melt and not only increase the time of restoration of normal conditions thereby, but also expose otherwise fire-protected compound to the flames, thus adding to the conflagration. A substitute for this material should be given consideration. The practice is increasing of completely enclosing control connections on metalclad switchgear. Attention to this problem and to the further protection of any light mechanical details is well worth while.

Fig. 3 shows an example of the application of the principles of sectioning, etc., employed in a 33-kV substation using metalclad switchgear.

**Indoor open-type switchgear.**

The principles applying to this gear do not differ from those for the previous type, and no especial difficulty arises in the application of the fire-sectioning principles enunciated. Fig. 4 is an example of the application of these principles to an indoor 66-kV switchgear arrangement.

**Outdoor switchgear.**

In outdoor switchgear arrangements again no change in principle is involved, except that wide spacing of groups may be relied on for fire segregation instead of actual walls. With such arrangements a screened ballast surround has been proved of great advantage as an oil-drain and fire-quencher, which has the further advantage of restricting the fire to a circumscribed area and thus facilitating its attack. Cable groups can be conveniently laid below this surround.

Where adequate spacing of plant cannot be secured, barrier division walls must be relied on, as for indoor gear. Whilst the consequential effect of fire on details is difficult to restrict in outdoor open-type gear, it has the advantage of comparative ease of reconstruction.

Outdoor metalclad gear possesses the advantage given by its excellent fire-resisting properties; but, having close spacing of panels, the treatment is similar to the forms shown in Figs. 1(*e*) and 1(*f*), the wall between sections being replaced by wide spacing.

## BUILDING ARRANGEMENTS: OIL DRAINAGE

As they are required as fire enclosures, buildings ought to be of fireproof construction. This requires a suitable building material, and where steelwork is employed it should be protected. In the author's experience brick walls of ordinary form have excellent fire-resisting properties, and no case of collapse from oil fire has come to his notice. Reinforced-concrete construction also appears satisfactory.

Pitched roofs supported by unprotected steel trusses should be protected by a fire-resisting inner ceiling.

Reinforced-concrete roofs and floors appear satisfactory provided all steelwork has a covering of at least 2 in. of concrete. For covering steelwork, sprayed or block asbestos is probably superior to concrete. Further, it is probable that ordinary reinforced-concrete ceilings with heavy loading on the floor above would not withstand prolonged and fierce oil fires, in which case a treatment of about $\frac{3}{4}$ in. of sprayed asbestos on the underside would be of advantage, although it must be admitted that no record of failures in actual power-supply experience can be produced to justify such special treatment.

In the practice with which the author is directly associated 9-in. brick (or more, if required structurally) is usually employed for walls with reinforced-concrete roofs carried on steel beams haunched in concrete. Alternatively, the construction is of the steel-frame type with brick or concrete panels, and in such an arrangement the steel columns and joists are covered with brick or concrete. This matter will be referred to again later, under the heading "Explosions."

All windows should be of wired glass, and all internal doors of fireproof self-closing design. The form of door employing steel-sheeted hardwood or sheet-steel covers packed with some form of insulating medium is very satisfactory. Simple 2-in. hardwood doors have also proved satisfactory in service as these usually char to a depth of about $\frac{1}{4}$ in. only, further combustion being stopped by the protective coating so formed. The alternative form must, however, be more positive and lasting. It is preferable that doors between fire sections should be sealed against oil flow by a small sill or other means. Where possible, such doors should be avoided.

Naturally it is desirable, where oil fires are in consideration, that means should be provided for draining off surplus oil in a safe manner. The minimum provision here is a suitably graded floor with drainholes to the outside air. Except where no likelihood of external fire exists such drainholes should be designed to quench burning oil, the simplest arrangement being a trap filled with gravel or screened rubble. Frequently switchgear details prevent the smooth grading of a complete floor, and in such instances it is usually possible to grade quite satisfactorily between switch standards. In the larger work it is sometimes necessary to provide, as complementary to floor grading, a piped drainage system similar to a scheme of water drainage. In such cases the final outflow may be to a specially arranged rubble sump, although the rarity of the occurrence of fire makes the manner of final disposal of little importance. For smaller switchgear, containing but a few gallons of oil per circuit breaker, drainage facilities are generally unnecessary, since the oil if discharged naturally will tend to be restricted to a small area by the roughness of the floor.

## FIRE FIGHTING

The minimum and essential requirement in fire-fighting is that the responsible executives should be advised of the location and telephone numbers of the nearest public or private fire stations both directly and by notices displayed at suitable points, and further that representatives of the supply authority should personally examine the

equipment available at these stations, as it is often woefully inadequate for dealing with oil fires.

The next essential is that hand extinguishers of the tetrachloride, methyl bromide, $CO_2$, or chemical-foam type should be provided at each station in convenient positions, as many fires can be quenched easily in their early stages. Such positions should never be inside the chamber in consideration (except in attended operating rooms). This remark may seem unnecessary, but experience shows otherwise.

For the lesser substations these provisions seem adequate. For the larger and more important stations, i.e. for power stations and major substations of similar importance, more elaborate precautions will frequently be justified and automatic fire equipments or, at attended stations, remotely-controlled fire equipments, may be employed. Such equipments should include alarm devices and notices to warn men working in the area to leave, and to close doors.

For fire-fighting where large quantities of oil may be immediately involved, e.g. transformer fires, or where oil may spray on to hot pipes, the author has a slight preference for a fixed installation—where possible of the high-pressure water-spray type. This is extremely rapid in its operation and possesses in some measure at least a quality not possessed by other types, namely cooling capacity. The most violent and difficult type of oil fire to deal with is that in which the oil is first brought up to the flash point and then ignited. The whole body of the oil is then practically spontaneously combustible and, apart from direct quenching of the flames, must be cooled to prevent re-ignition. Transformers are peculiarly susceptible to faults between turns, which may produce this condition of the oil. It is necessary also to bear in mind that where a transformer has caught fire it is as a rule of little further importance that its insulation might be damaged by water.

A similarly difficult condition is that which arises where a burst pressure oil-pipe discharges on to hot pipes or other hot parts. This kind of occurrence has been responsible for some of the most serious fires in the industry, since the oil is being continuously discharged on to an ignition device. Here a cooling property in the fire attack is highly desirable, and even the normal water hose may be of assistance.

For switchgear, unless this is of the completely enclosed type, the use of water may be undesirable where suitable alternatives are available. The author prefers, for fixed fire equipment for application to indoor switchgear, the use of $CO_2$ or methyl-bromide installations with saponine foam as an alternative, and, for outdoor switchgear, saponine foam. Saponine-foam or water-spray installations require a water pressure at the branch pipe of about 50 lb. per sq. in. or upwards. Where special pumps have to be installed for this purpose care should be taken that the source of power is not itself vulnerable to the loss of supply which it seeks to limit.

Water storage tanks employing compressed air for discharge purposes are a satisfactory arrangement for many installations.

In all power stations the author suggests that fire equipment should include high-pressure water mains with the usual branch pipes and, in addition, special branch-pipe equipment of the foam or water-spray type. Portable equipment of the types already indicated completes the installation.

For automatic installations, trip devices consisting of controls held off by chains with thermal melting links may be used, as also may simple combustible rope providing precautions are observed against normal stretching, etc. There are also excellent liquid-filled glass containers available for this type of work, arranged to burst at a given temperature and thus release the necessary controls.

## TRANSFORMERS

Whilst the general principles enumerated already apply equally to transformers, it is suggested that, in view of the large quantities of oil involved, it is desirable in general to go beyond mere group sectioning and to adopt unit sectioning, preferably in independent chambers.

The pier type of foundation, as opposed to the complete raft, is very suitable for transformers and has the advantage that it permits a large part of the area immediately below the transformer to be filled with screened rubble to act as a fire-quencher and assist oil drainage. All large transformers could with advantage be provided with protective relays of the gas-collection type or, failing this, ought at least to be fitted with oil-temperature alarms.

Where possible, indoor transformers should be mounted in chambers adjacent to outer walls and opening to the outside. Alternatively, in special cases of the smaller sizes the use of direct air-cooled transformers may be considered.

Investigation abroad is pursuing the production of a non-inflammable alternative to oil, and some success has been achieved with substances such as Pyranol for use with transformers. These may offer an alternative to the air-cooled transformers suggested above. Pyranol is costly and has many unusual properties, so that it would appear to be suited to small transformers only and to require further investigation and experience before it could be recommended freely. Incidentally, it is not suited to circuit-breaker work, and also requires special insulating materials as it attacks normal insulations.

Means of closing ventilating outlets may be of advantage in indoor transformer chambers. Where relatively large oil-immersed transformers must be mounted in indoor chambers it is desirable to consider very carefully the consequential damage possible from oil fires, and to stiffen precautions accordingly. The use of automatic fire apparatus has much to commend it in difficult cases.

For outdoor transformers a screened-ballast surround is desirable, 12 in. to 18 in. deep, with drainage, and where transformers are necessarily placed in close proximity intermediate barrier walls may be necessary. In such layouts, and indeed in any arrangement of fire-sectioning, it should always be borne in mind that in attacking a fire the local brigade is likely to spill much water about; duplicate items of plant should, if possible, be so arranged that the attack on one item does not jeopardize its duplicate. In this connection the use of cable sealing terminals instead of the open type is now to be recommended where commercial and practical considerations permit. A few years ago such could not

be entirely depended upon for the higher voltages and had also the disadvantage of being difficult to deal with if it was desired to remove a transformer. Both these objections can now be met in many instances.

In view of later remarks under the heading " Explosions " it is noteworthy that the author has no experience of explosions accompanying transformer failures being of such violence as to produce building failure.

## REACTORS

The treatment of reactor banks of the oil-immersed type is similar to that of transformers.

There is one important point in the use of reactors which is worthy of note. The use of busbar or group-feeder reactors necessarily implies the splitting-up of a system into a series of independent sub-systems, since such reactors must not in general be short-circuited by the external coupling of feeders from different reactor sections. Since these sub-areas are independent, each must be treated as a separate system in design, and each section of busbar defined by the reactors must be independently subjected to the same principles of electrical and fire sectioning as apply to any single system. Fig. 5 shows diagrammatically two examples of power-station switchgear arrangements which meet this requirement. In Fig. 5(*a*) the barriers enclosing the reactor section switches are not essential but reduce the liability to consequential damage. In practice these particular barriers rise to loaded-crane clearance height only. Fig. 5(*b*) is interesting because although it is generally similar to Fig. 5(*a*) the use of two circuit breakers for each generator makes necessary the addition of special isolating links outside the switchgear chambers, as otherwise a fire in one fire section might result in loss of the generator unnecessarily.

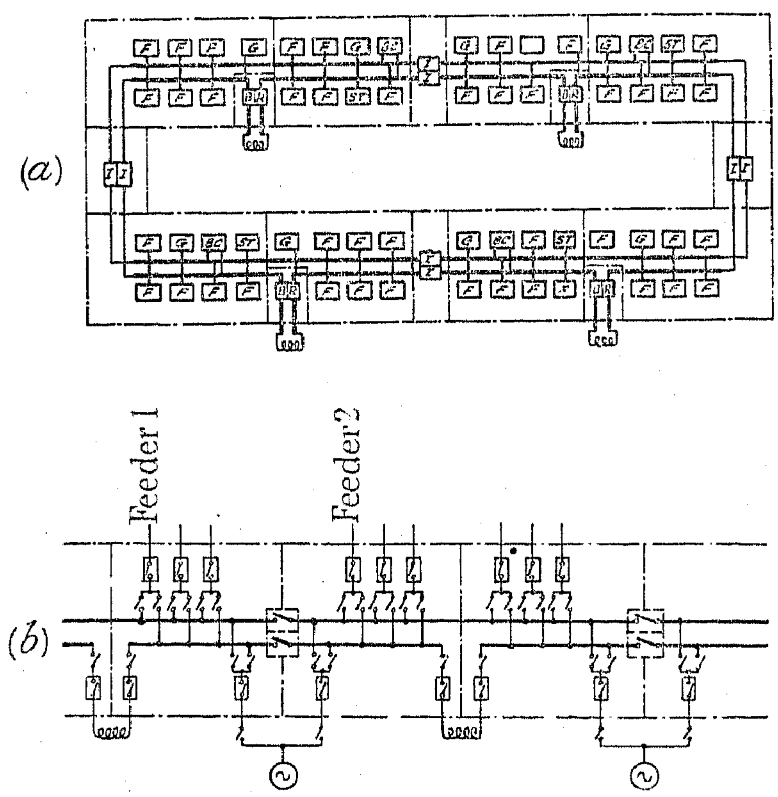


**Fig. 5**

G = Generator circuit-breaker.
BC = Busbar-coupler circuit-breaker.
BR = Busbar-section and reactor circuit-breaker.
ST = Station-transformer circuit-breaker.
F = Feeder circuit-breaker.
I = Oil-immersed isolator.
— —· Fire-sectioning walls and partitions.

## GENERATING PLANT

In their application to generating plant the fire-precaution principles remain unaltered, although the perspective may change somewhat. The only ultimate safeguard against unsupportable loss of generating plant by fire lies in subdivision. For reasons of cost such subdivision is difficult, though not impossible, in single generating stations. In the full development of a site, however, it is possible, and indeed quite natural, to erect successive stations as effectively-separated stations. The rest is or ought to be provided by the national grid, which, by the interconnection it provides, should enable the complete loss of any single station to be supported without other than short-time interference with supplies.

This leads to an important point. It has not been suggested that for a remote emergency like a major fire no " black-out " should be permitted. On the contrary, it is strongly asserted that the attempt to preclude a black-out entirely in such an extreme emergency is, despite the statements of the popular Press, directly contrary to the public interest, since it involves excessive expenditure which must be reflected in the ultimate price. It is, however, suggested that such an interruption ought to be of short duration only. For this reason it is desirable to emphasize that in any power station the main switchgear is, in a truly interconnected system, of more importance than the station, and that there is no excuse in a major station for imperfect attention to the details of electrical and fire sectioning of switchgear touched on in the paper. This is particularly important where, as is usually the fact, a power station forms not only a generation contribution to the grid but also the independent focal centre of a local distribution system.

## EXPLOSIONS

In any consideration of the fire risk the risk of explosion must be included. The principles of treatment are unaltered, but certain details require emphasis.

Explosions in electrical plant may occur owing to direct failure of circuit breakers resulting from inadequate capacity, or as the result of arcing in open-type gear; secondary gas explosions may arise from uninterrupted insulation failures in oil-filled or compound-filled apparatus, switchgear, instrument transformers, cable terminals, etc.

Improved understanding of circuit-breaker technique, and particularly proper short-circuit testing, is doing much to reduce the circuit-breaker risk to acceptable dimensions. Insulation failure is, in the author's view, the most important consideration of all.

More serious disasters occur owing to simple insulation failure than to any other cause. A special type of transformer failure has already been mentioned in this category and has been discussed. Insulation failures of the more general type are usually covered by satisfactory protection. Where such protection is not provided or is not available a failure may be followed by heating of oil until combustion occurs with or without explosion or, alternatively, may produce in certain examples gasification and breakdown of the oil followed ultimately by

ignition of an explosive mixture. A particular form of this is referred to later under the heading "Busbar Protection."

The simple failure of a circuit breaker to clear a fault is usually accompanied by an explosion and usually followed by a fire of great or small dimensions. The author has, however, no direct knowledge of such a failure producing explosive forces of sufficient intensity to destroy a building, although doors and sometimes windows are blown out. On the other hand, where the gas explosion has followed an unprotected insulation failure the explosive forces seem to be much more violent, probably owing to relatively slow gas-collection, and in the three principal examples of building destruction of which the author has personal knowledge it was concluded from the evidence that the failures had been of this type.

In the most recent of these the author made some not very reliable calculations to estimate the forces which had been at play, on a static basis, and arrived at a figure of not less than 15 lb. per sq. in. This figure is too large to be supported by brick or even steel-frame buildings of conventional types. Investigations are continuing in this matter, but pending the result of these it is suggested that at least one wall parallel to the gear should contain ample windows or doors, secured no more strongly than is necessary for weatherproofing and to prevent access of unqualified persons. These it is hoped, following on experience, will act as relief vents for explosions and secure the safety of the major structure.

One important point is clear, however, and that is that distinct buildings are preferable to buildings divided by barrier walls. Quite small separation, a few feet only, would seem satisfactory, as the masonry is usually merely overturned. System engineers, however, will be only too well aware that site limitations enter in very frequently and that even such separation may be difficult. The principle can, however, be maintained by using double or specially-strengthened barrier walls and frequently by making a deliberate break in the roof or wall material at these points so that the bursting forces are not transferred by a tearing action to adjacent fire-section walls or roof.

## BUSBAR PROTECTION

The need of sound plant and sound protective gear has already been referred to. On the plant side the technique and standard is steadily improving, subject occasionally to setbacks due to uncontrolled price-cutting. Good protective gear is also available.

There is one important zone which is not, however, generally provided with direct protection—the busbars. This zone usually includes in addition the circuit breakers themselves, the busbar isolators, and, most frequently, the feeder isolators. It is possible to provide partial protection for this zone by lightly insulating the switchgear from earth and from the associated cables and employing a fault device to operate when current flows through a single earth connection, or alternatively by employing a system of protection which balances all the currents to and from the busbars and which again requires insulation of cable-sheaths from the switchgear. Finally, a system of time-graded leakage protection can be employed. The problem is actually much more complex than many of its advocates realize, and there are several weaknesses to guard against. It is clearly most important that no system of busbar protection should impair the reliability of supply. For example, it is desirable to employ two master relays in series for the final tripping control, so that no inadvertent operation during maintenance or otherwise shall produce operation. Again, one serious difficulty lies in guaranteeing that the remote end of connected feeders shall be cleared when a busbar fault occurs, as otherwise only 50 per cent of busbar faults are provided against. Where the feeder protection is of the impedance type this requirement is sometimes met directly; if of the pilot type it is possible, with certain complications, to secure it. Again, time-graded feeder protection will usually meet this point, but long-time grading of several seconds is imperative and, since the busbar protective arrangements proposed are all of the earth-fault type, time-delays of this order introduce the danger of phase faults.

A study of the past records of electric supply has not indicated that any material direct risk exists to the public at large from major substation failures. No single example has come to the author's notice in which a major substation fire in this country has produced any serious consequential fire or damage to other property or persons. Inadvertent loss of supplies due to unsatisfactory busbar protection may, however, imply certain indirect risks to the public, as in pumping and ventilation of mines, supplies to hospitals, etc. Finally, the author has no knowledge of busbar or circuit-breaker failures producing injury to operators which might have been prevented by busbar protection. Based on actual experience, therefore, which must be the ultimate arbiter of the supply engineer, the problem is primarily one of security of supply, and we must be satisfied that additional protective gear of this type will give such added security. Protective gear cannot prevent failures, and may produce them.

If a busbar fault occurs, disconnection of all the circuits connected to that busbar is inevitable, whether by busbar protective devices or by hand. Assuming that the general provisions discussed in this paper have been met, the function of busbar protection is therefore to limit the period following a fault during which emergency but complete conditions of supply exist, lest further electrical faults produce definite and long-time interruptions. Since the average incidence of this emergency in a particular substation may be of the order of 1 in 100 years, it is clear that we are not justified in introducing any equipment for this purpose unless we are sure that it is not itself going to introduce added risks of interruption. The author's outlook is, therefore, that whilst academically the principle of busbar protection is sound, practically he requires very solid guarantees that the form of protection proposed is nearly foolproof, and frankly he is somewhat undecided on this point. So long as items of plant are dealt with as units, coincidence is necessary to secure interruption in a duplicate system, and in adopting busbar protection he has an uneasy feeling that we may be putting the "eggs" back into the one basket. He is at the same time satisfied that, if the precautions dealt with in this paper are applied, no serious risk to supplies exists where busbar protection is not provided.

## HEATING OF SWITCH CHAMBERS

A most important source of insulation failures is the presence of moisture due to condensation. All important high-voltage switch-houses should be provided with heating, automatically controlled or otherwise, to maintain the temperature of the air of switch chambers above the dew point. Periodical tests of oil are desirable to check this condition. Quite simple tests such as a "crackle" test or copper-sulphate test are satisfactory. Circuit-breaker insulation failure following some time after successful clearance of a fault is also not uncommon, and routine inspection of circuit breakers as soon as possible after fault operation is very desirable.

## SMALL-OIL-CONTENT CIRCUIT BREAKERS

The important tendency at present to reduce the oil content of circuit breakers is all to the good, but it must not be assumed to represent the whole of the story. If a fire originates from the failure to clear of a circuit breaker the accompanying explosion occasionally shatters the tank, but much more usually, particularly with the better-class switchgear employing strong tanks, simply deforms the structure as a whole, with brief emission of oil and gas through strained joints, relief vents, etc.

Where the tank is shattered, given proper drainage facilities the surplus oil will be rapidly drained off and the following fire will differ little in its intensity whether the tanks hold 100 per cent or 50 per cent oil. In the more usual case in which the structure is strained the external surface burning will not differ greatly from that in the first case but much of the oil in the tank will be retained and will continue to burn in wick form, impeded by the tank top and other parts, and also, in indoor working, by its own smoke development. The subsequent burning here is then proportional rather to surface area, i.e. tank diameter, than to volume of oil, and since a few gallons of oil will burn in this manner for a long period the actual volume of oil is apt to be of major consequence only where the fire attack is delayed for some considerable time. It should be remembered in this connection that, given metalclad switchgear, experience clearly shows that the contribution to fire intensity of switch equipments other than that primarily affected is extraordinarily low.

On the Continent the development of the oil-less circuit breaker is of considerable interest. This has taken two forms, the expansion or water-type circuit breaker and the air-blast circuit breaker. These possess, like all types, certain inherent difficulties of their own which will no doubt be dealt with or eliminated in the normal progress of design.

In the special consideration of fire arrangements, however, it has already been pointed out that insulation failure is the principal cause of fires and that with modern circuit-breaker testing we can hope to reduce circuit-breaker failures to a very small proportion of the whole. Oil-less circuit breakers alone, therefore, only constitute a reply to a lesser part of the problem. The chief present objection to these types is that they do not lend themselves to the principles involved in metalclad design and direct interlocking, which in the author's opinion have contributed in a very large degree to safety of operators, reliability of supply, reduction of cost, and the limitation of spread of fire from one equipment to another. He would in no sense abandon these features in favour of relatively minor improvements in circuit-breaker oil-content.

The author hopes that this side of the problem will receive particular consideration as, given its satisfactory solution together with that of the other minor matters which will certainly be cleared up in the ordinary course of development, this form will provide a real additional contribution to the art.

He would stress, however, that with present forms of circuit breaker all the safeguards necessary in reasonable engineering can be satisfactorily achieved by attention to the details of arrangement.

## GENERAL

An important factor in any oil-fire fighting arrangement is the dense black smoke which impedes or prohibits access to the seat of the fire. This is a most serious consideration in dealing with fires which occur in the inner regions of large power stations, for example, and for this reason it is strongly recommended that where possible, and except where small size plant only is in question, all large transformers or switchgear should be mounted in separate buildings or in chambers opening to the outer air and sealed off from the inner side. Where this is not possible automatic or remote-controlled forms of fire attack should always be employed, to make possible immediate attack on the fire without actual access being necessary.

A second important matter in all electrical failures is to eliminate the electrical contribution to the fire as rapidly as possible by tripping the switches connected to the affected busbars and the corresponding remote feeder switches. If a sound basis can be found for doing this automatically so much to the good, but in any case operating instructions ought to provide for immediate action of this type, starting with the section switches, whenever a fire or explosion occurs.

Since prevention is better than cure it would naturally be preferable to anticipate, by routine insulation-testing, the failures which produce fire. Unfortunately no form of routine insulation-testing has yet been devised which has not important objections.

The most promising form at present is what is known in America as Doble testing, which makes routine field tests of watts loss and power factor with a special portable apparatus, and compares these one against another and all against continuous records of past testing.

Unfortunately, for certain physical reasons, there are at present some limitations in the application of this to metalclad switch equipments, but developments are proceeding with very promising results, and it is now probable that Doble testing will provide a useful auxiliary to other provisions.

In conclusion, the author wishes to express his thanks to many colleagues of the staff of Messrs. Merz and McLellan for their valuable assistance in drawing up this paper.

## DISCUSSION BEFORE THE INSTITUTION, 11TH FEBRUARY, 1937

**Mr. F. Forrest:** I am glad that the author does not attempt to exaggerate the twin risks of explosion and fire in our generating stations and major substations; because, while those risks exist and it is important to guard against them, they are ones which any insurance company would be glad to carry at a small annual premium. Nevertheless, with the growth of electric supply undertakings the consequences of even a temporary stoppage of supply are so important that every possible step must be taken to ensure that fire does not occur at all, or, if it does, that it is put out in the minimum possible time and with the minimum disturbance. Regular inspection and testing of the switchgear should therefore be a recognized part of the work of those controlling power stations and substations, and the switchgear installed must on every circuit be of such capacity that it can break the maximum possible short-circuit current. This indicates that we must, where necessary, install current-limiting reactors.

In existing stations and major substations the problem is much more difficult to tackle than where one is starting *de novo*. I know of no better means of subdividing a switch house into sections than by means of fireproof walls of adequate thickness (not less than 9 in.), with fireproof self-closing doors. I have a preference for open-type switchgear so arranged that we get a fireproof division between each oil switch and its neighbour; this lends itself also to a better disposition of the switch itself, in that whilst the top portion of the switch may be inside the house the tank can be arranged below the floor so that it is out in the open air. In any case, in the ordinary open-type cubicle switchgear the bottom of the cubicle should be dish-shaped, and the bottom of the dish should conduct any spilt oil into a pipe running outside the building. In open-type switchgear all busbar and copper connections should be thoroughly insulated with micanite tubing, so that conducting vapours which may be given off after the explosion shall not create short-circuits in the main circuits.

With regard to fire-fighting equipment to be installed in power stations and major substations, the fire brigade should be called into conference and their officers should advise as to the type and disposition of the apparatus to be installed. The brigade should regularly inspect and occasionally test the apparatus, and should familiarize themselves with the station and the means of gaining access to it in case of emergency. As a last resort there is nothing better than a high-pressure water jet for putting out an oil fire. This means that we have to face the issue of shutting down a whole section of the switchgear in order that the hydrant may be brought to bear on the seat of the fire. It is better to face such a situation of grave emergency boldly and to bring the water jet into operation early rather than to attempt to put the fire out with some means which are perhaps not so effective and give the fire a chance of getting a firm hold.

With regard to $CO_2$ apparatus—the emulsifier and other types—this is all designed on the assumption that the fire will occur at a conveniently low level near to the floor, whereas my experience has been that fires occur on the wall or ceiling, in which case such apparatus is of no use, and is in fact dangerous to the operator.

Transformers should be placed out of doors wherever possible, and I go so far as to recommend that in connection with major substations for converting from alternating current to direct current it would be better not to have transformers at all, and to adopt the motor convertor rather than the rotary convertor or the rectifier. This is what we have done in Birmingham. For large transformers I am inclined to recommend the adoption of the Buchholz relay, which has now been well tried out and enables a transformer which has developed a fault between turns to be tripped out automatically before further damage is done. With regard to new stations and new switch-houses, I agree with the author that it would be better to have complete separation of switch-houses rather than to divide one switch-house into a number of sections. I believe that future designs of major power stations will include a number of separate switch-houses each divided from the next by a considerable distance; and probably the centre of each such house will coincide with the centre of the turbo-alternator. Each of these small switch-houses would contain a main controlling switch for the turbo-alternator and a number of breaker feeders, and would be connected to the adjacent switch-house by means of a busbar running through a tunnel closed by fireproof doors at each end. The fact that we are contemplating going to a great deal of expense to deal with large oil switches and oil-cooled transformers makes one feel that it would be as well if our switchgear manufacturers endeavoured, like those on the Continent, to develop switches which do not contain oil. Future developments may produce switchgear which will enable us to do away with the fire risk associated with the switch itself. In my view it should be a standing instruction to operating staffs in big power stations that, if a fire occurs on any section of the switchgear, that section must be switched out, laid dead for a period, the various fire-fighting means tried, and, last and most drastic, but most certain of all, a fire hydrant should be put to work.

**Mr. H. W. Swann:** I am glad that the author draws attention to (*a*) busbar-zone protection and (*b*) fire fighting.

On page 298 he says that an important consideration is "to eliminate the electrical contribution to the fire as rapidly as possible." I take this as fundamental, and I think it implies some form of automatic quick-acting busbar-zone protection to prevent persistence and the consequent destructive fire.

The author, to use his own word, seems inclined to treat busbar zone protection as an "academic" consideration, but the failures of high-voltage insulation which have occurred in the past 12 months and earlier indicate "danger" in the sense in which that word is used in the Home Office Electricity Regulations, and the time may be approaching when legal interest in this point will arise. Excess-current protection may be demanded by law if it can be shown that its omission results in danger. I realize, however, that the fear of unwanted operation of trip gear and protective devices must be and must remain

a first consideration. The development of busbar-zone protection should therefore be a gradual process leading to a technique as nearly perfect as that which has been built up for the protection of transformers, generators, feeders, and other parts of the electrical system of to-day.

This leads me to the consideration of the rating of system earthing resistances and earthing transformers. The time/current rating of such apparatus is, and has been in the past, determined by the setting of the various protective devices of the system and their ability to take care of phase-to-earth faults and short-circuits. If the time rating of those resistances is so determined, to be consistent one should also take into account the amount of power which can be dissipated in a busbar-zone fault, and its duration. If persistence is tolerated this will necessitate earthing-resistor capacities out of all proportion to what is common practice to-day. The alternative, of course, is some selective form of automatic busbar protection.

I do not think, however, that a first-class base-load selected station is a proper place in which to experiment with busbar-zone automatic protection. Stations of lesser importance, or where extensions are being planned, are places where experience can be acquired and technique developed.

The E.R.A. have set up a committee which is trying to find out the best way of dealing with electrical fires, having regard to the situation and conditions under which they occur. It has been apparent to my Department for some time that ideas vary. Manufacturers usually have one particular type of apparatus to sell, and they perhaps naturally claim that it is effective under almost every condition of use. We think it might be possible to lay down a set of conditions and situations and to prescribe the best form of fire-fighting equipment for those conditions.

I want to emphasize that the peace-time considerations which affect the planning of major switchgear equipment really coincide with war-time requirements. The Air Raid Precautions Department of the Home Office attaches enormous importance to electrical supply in this country. Wide separation of switch houses (and the author says that the switch house is the most important part of the station) not only suits the stability of supply and limits the destructive effect of fire, but it is also advocated by the Air Raid Precautions Department and is the best precaution against the effects of air attack.

The idea of connecting undertakings to the grid at more than one point is not a new one. Several of the larger undertakings in this country are connected to the grid at a number of points. The expense of doing this in every case would be so colossal as to be idiotic, but the possibility should be considered when the importance of a load is such as to justify more than one grid connection. There will be many towns and areas where the load, in consequence of the demands either of factories or of other services, will warrant the consideration of large extensions, and the provision of new switch-houses. In such cases is it not reasonable from every aspect to consider whether the time has come to take the eggs out of one basket and put them into two?

**Mr. H. W. Clothier:** The author says that he has no knowledge of "busbar or circuit-breaker failures producing injury to operators which might have been prevented by busbar protection." I have no information to the contrary, but there have been a few flashovers caused by thoughtless actions of operators. No automatic protection can be fast enough on high-voltage circuits to prevent the first momentary shock or burns, and so an operator would run a risk of injury whether busbar protection were there or not; but on the other hand a good protective scheme may reduce consequential effects.

The author fears added risks of interruption due to inadvertent operation of automatic protection, and candidly weighs the pros and cons of the question. He requires to know that the protective system is "nearly foolproof," and "frankly he is somewhat undecided on the point." Thus, as I understand it, he throws down the glove to designers, and an examination in detail of the many available systems will doubtless be the response. Suffice it to say that satisfactory forms of protection have been devised, and that I believe they will sooner or later be accepted with no more question than other well-known systems of unit protection for instantaneous isolation of faults in cables and plant where these have been proved reliable and in consequence are now considered to be indispensable. Technical perfection demands instantaneous isolation of all earth faults, but if this is ruled out on the score of cost considerable use can be made of a short-time discriminating leakage device, e.g. "back up" protection for substations and, in the simplest form for power stations (although the method is somewhat incomplete), the temporary opening of the neutral-to-earth circuit.

As the author explains, serious fires in major stations are of very rare occurrence. When they do happen, however, they weigh heavily upon all grades of persons within the range of responsibility whether they be users or manufacturers. The very rarity of the initial faults is one reason for the risk of damage becoming extensive, because operators may be unprepared for the right action in an emergency. Over the last 25 to 30 years my company alone has installed over 25 000 metalclad substation and power-station panels, rated at 6 000 volts and over, and there must be in all some 100 000 (including all makes) in use. Comparatively, the number of fires has been negligible. In fact, 12 months ago I would have said that busbar-zone protection, although largely used in America and justified for open-type switchgear, was a complication unnecessary on metalclad switchgear. That decision was taken over 30 years ago—indeed, after the first metalclad 6 000-volt switchgear ever made had been actually fitted with Merz–Price current-balance busbar protection—and it held until the occurrence of a recent major power-station fire incident. The future conditions of such existing stations may not be easier in this connection. Indeed, some may be working under heavier conditions than in the past, and it is known from modern testing-station experience that the numerous circuit breakers that have been supplied in the past are not up to the standard of those made and tested to-day to the maximum of present service requirements.

I have studied all particulars of fires so far as they are available to an independent manufacturer, and I have found that, starting from the one at Bristol in 1903, the few that may be classed as disasters became so because

of sustained arcing following the initial failure. An overstressed circuit breaker operating on a fault may throw off its tank without doing much more damage than splashing oil in all directions; the real danger of fire arises when there is insulation failure and exposed conductors continue to arc to earth or, worse still, between phases. The effects of such dangerous arcing are best avoided by automatic isolation. I agree with the author's statements about metalclad switchgear. Even explosion risks, which are very remote, may not be reduced by the use of open-type conductors. In my opinion the placing of micarta or other organic insulation substances over the busbars is not a complete remedy for the danger of an initial fault causing arcs spreading from one place to another. Moreover, the generation of explosive gases accompanies the presence of all organic substances that are within range of the arc. I have recently had some comparisons made of arcing on conduction inside steel tubes with different kinds of fillings, namely air, oil, and compounds, and it was surprising to find as much as 25 per cent of methane in the gas produced by simple arcing in the air-filled example.

My conclusion is that the more technically perfect the switchgear and connections thereto the less the need for protection; but there will always be a risk, even in modern gear, of some initial defect in insulation, or of some subsequent failure in operation or maintenance, tending to set up sustained arcing, and prevention by automatic protection is as important as fire-extinction and fire-limiting precautions.

Replying to the author's plea for an investigation of possible improvements in the fire-resisting properties of control cable, I have in my possession a sample of a 7-core control cable that will not burn at any temperature below the melting point of copper.

**Mr. H. Hoyle:** On page 290 the author mentions "Provisions which whilst not essential are desirable and should be applied where the importance of special conditions of the station justify the expenditure." I submit that the case for the installation of fixed fire-protection equipment in power stations is unanswerable in view of the fact that power stations can be protected against serious fire at a cost which is negligibly small when compared with other items of expenditure. Is the engineer more prepared to accept the responsibility of fire in his station than the business man is prepared to do in his factory? Public and private business concerns have been installing fixed systems of fire protection for a longer period of time than the electrical industry has been established, and they do not do it for philanthropic reasons but in order to safeguard their financial interests. Of how much greater importance, then, is it that the power-station engineer should protect his station, for he has to render a service to the community in addition to protecting his plant.

Mr. Forrest made reference to the extinguishing of oil fires by the use of water from a hydrant, whereas the author makes reference to the water-spray system. To use water in the ordinary sense is not satisfactory for the extinguishing of an oil fire. Water-spray systems of many kinds were tried out for a large number of years but they all failed, until a system was discovered whereby water could be applied in the form of fine powerful streams which, on impact with the surface, formed an emulsified mixture of oil and water which would not burn. This system was first approved for a power-station fire-protection installation by Sir Leonard Pearce, and the system has since been widely developed for the protection of turbo-alternator lubrication plant, transformers, and switchgear, in this country and abroad.

Gas is mentioned for the protection of certain equipments; I would point out that we in this country have not had as much experience with the carbon-dioxide systems as the Americans have had. In America, $CO_2$ has been employed to a large extent for the protection of several classes of industrial plant. Its use is governed by regulations.

Methyl bromide is suggested as a fixed installation for certain parts of the premises. My own opinion is that it is unsatisfactory under such conditions.

Brick walls form very satisfactory fire-resisting barriers, and the best type of fireproof door is that which employs a wooden core, suitably sterilized, and covered with sheet steel to prevent access of atmospheric oxygen. Such a door will withstand very high temperatures for very long periods of time, provided the fittings are of suitable material. It is of very little service to provide a door which will resist fire if the fittings which support it will fail either as a result of the fire or as the result of being cooled rapidly by water discharged from the hoses of the fire brigade.

**Mr. J. Hacking:** I think it would have led to a rather more consistent analysis if the author had made it clear that fire precautions divide themselves naturally into three sections: (1) prevention of fire; (2) isolation of fire; and (3) extinction of fire.

I want to raise a question in connection with prevention. Most electrical fires are started by arcing, but it is the general experience that fire does not result unless the arcing is unduly prolonged or there is combustible material in the immediate neighbourhood of the arcing. Many insulating materials are combustible and, as the author points out, practically all fires are started by insulation failure. Some insulating materials are, however, more inflammable than others, the worst being oils and compounds. It may be expected that, with an equal standard of insulation, fires are more likely to start on designs of switchgear which have large quantities of free oil in close proximity to the major insulation; and in this respect many of the designs of metalclad switchgear are at a disadvantage compared with open-type switchgear. Designers of metalclad switchgear should devote more attention to the reduction of the amount of free oil in the neighbourhood of the busbars and the connecting devices.

There is another point in regard to which metalclad switchgear is slightly at a disadvantage as compared with open-type switchgear from a fire-risk point of view, and which comes into the category of isolation. With metalclad switchgear, isolators are inevitably directly associated with the switches, and a fire on a switch may well affect both sides of the isolating device. This is illustrated by Fig. 1(*d*) in the paper, which shows a fairly common arrangement of fire sectioning. If it had been more universally applied in this country there would be less risk of prolonged interruption of supplies than is the

case at the present time. As the author points out, however, it is not complete, and the chief reason for this is that a fire starting in the busbar section switch may quite well affect both busbar spouts and thereby put out of commission both halves of the busbar. This danger would not exist if the isolating devices were outside the chamber containing the switch—the natural arrangement which obtains in open-type gear. Although we should not ignore the increased fire hazard of metalclad gear, we should not allow this to outweigh the important advantages of this type of gear in other directions. The disadvantages I have mentioned are not of serious consequence provided the equipment is sectioned in the manner suggested by the author.

Turning to the question of busbar protection, Mr. Swann has voiced the prevailing impression that busbar protection is a relatively new device. This is very far from being the case. As Mr. Clothier mentioned, the first metalclad board was actually provided with busbar protection. This was at the time (about 30 years ago) when Merz–Price protective gear was being developed, and it was obvious that this had great possibilities of application to the busbars. The complication of this type of protection was so great, however, that it was not considered practical politics to extend its use. Since then we have become accustomed to an ever-increasing complexity in our protective systems, and I think it is quite possible that in the next few years there will be greater application of busbar protection, particularly at stations which are unattended. There are already in existence a fair number of applications of busbar protection at substations, and I am glad to hear Mr. Swann say that he does not think busbar protection should be applied to major power stations at present. In the absence of such protection, however, the operating staff should realize the dangers attendant on a fault in the unprotected zone, and at the first signs of such a fault they should not hesitate to isolate the faulty section, even at the risk of interruption of supply. In view of the inflammable and explosive nature of the oil and compound it is the height of folly to attempt to fight a fire without cutting off the supply.

I agree with the author that small-oil-content circuit breakers are not in themselves a complete solution of the fire problem. There was a case relatively recently in which a circuit breaker failed to clear, and arcing was set up inside the tank. The tank and its fixings were of very massive construction and showed no material signs of distress, but the elastic stretch of the bolts was apparently sufficient to allow oil spray, vapour, and flame to be ejected from the joint in the tank and through a joint in the oil vent pipe, resulting in a secondary explosion quite external to the switch, which blew off doors and windows. The total quantity of oil lost on this occasion was only 40 gallons, of which the majority was discharged outside the building; and a fault of that sort could, of course, quite readily occur with a small-oil-content breaker.

**Mr. C. H. Pike:** It seems to me that in the desire for larger transformer and switchgear units we have been putting too many eggs into one basket, and now, by adopting fire precautions, we are going back to the condition of putting them into different baskets. By adopting rather less interconnection we may tend to eliminate the long shutdowns which have occurred in the past.

The great purpose of electricity undertakings is to sell electricity, and in order to do that they must satisfy and please the consumer. It seems that we have many more failures than we should tolerate. We had two instances not long ago, both due to fire, in which the supplies to extensive areas were interrupted for periods of about an hour, and, unfortunately, round about dinner time; dinners spoilt by electrical breakdowns are not going to further our propaganda for cooking by electricity.

The avoidance of shutdowns implies the elimination of possible sources of fire and therefore the elimination of circuit breakers. The C.E.B. have very successfully eliminated breakers in many parts of their system. Modern supply systems tend to use too many circuit breakers—all of comparatively cheap design. By the adoption of group switching I think one can eliminate the possibility of long shutdowns. Mr. Clothier's paper* mentioned the American method of synchronizing the load instead of paralleling the busbars—the usual British practice. If we could possibly arrive at a compromise between our method and the American method we could reduce the maximum possible kVA to be broken by our circuit breakers, and then there would be less risk of fire.

Another point I should like to make is in connection with substation design. As the control boards are usually situated very close to transformers, in the event of transformer failure the control board would immediately be affected and the whole installation shut down. This should be the first consideration in the design of fire sectioning.

(*Communicated*) In connection with $CO_2$ automatic extinguishing apparatus, it is usual to fit safety locks to prevent operation whilst men are working in the vicinity. Should any trouble arise, the men involved would very naturally quit the danger zone without being able to bring the extinguishers into action, for in many situations this would be impossible; hence it should be possible to operate the safety lock at a point remote from the fire zone. Also a definite indicating device should be fitted in conjunction with the safety lock to prevent this from being left on inadvertently (which has happened, to my knowledge), thereby rendering the fire protection inoperative until this is discovered, which, in the case of unattended substations, may be after several days.

Could the author give an opinion as to the efficiency of the transformer protective device recently introduced, which operates by the variation of the anode current in a valve circuit due to the variation of the capacitance of a condenser fitted in the tank, when the dielectric changes owing to the presence of gas produced by an incipient fault?

The heating of switch chambers is of paramount importance and is often neglected. Some years ago it was suggested that manufacturers should incorporate some form of low-temperature heating in the metalclad switchgear itself for use in damp situations, but I am not aware that this idea has been adopted.

**Mr. J. R. Mortlock:** I will confine my remarks mainly to the question of condensation and its effect on insula-

* *Journal I.E.E.*, 1932, vol. 71, p. 285.

tion. A method of preventing condensation which has been used considerably is that of fitting local heaters at ingress points, and thus heating up the whole chamber to 10–15 deg. F. above the normal ambient temperature. This method is perfectly satisfactory provided the ambient temperature does not fall rapidly. An alternative method is to use de-humidified air—containing up to 10 per cent humidity as a maximum—and feed it into the chambers. Under these conditions condensation is physically impossible, provided the air supply is so maintained that there is always an outflow of air from the chambers. This has even been accomplished in such cases as spout orifices, where a fairly large outlet is available owing to the shutter gear giving a $\frac{1}{8}$-in. air-gap.

Recently in connection with some switchgear for installation in the tropics a comparison was made of the kilowatt-hours required from a heating point of view and the kilowatt-hours consumed by a de-humidifying equipment. In the case of the heating 650 kilowatt-hours were required daily, giving a safety factor of probably 95 per cent against condensation. With the alternative method the figure was 30 kilowatt-hours daily, with a safety factor of 100 per cent.

As regards power-factor testing of switchgear, this is in its infancy as yet and is subject to several difficulties because the power factor varies with the type of insulation and with the temperature.

**Mr. C. F. Bolton:** There may be many cases where the design and layout of existing stations do not permit the adoption of the fire-sectioning principles advocated in the paper, and therefore the engineer has to rely entirely on fire-fighting media. In that connection he is in some difficulty, because he has to approach the manufacturers of fire-extinguishing apparatus, each of whom advocates the use of the particular apparatus in which he specializes. The result is that, after making numerous inquiries, the engineer is apt to be left with some sense of confusion as to the best type to use for a particular risk. The same thing happens in some cases if the chief officer of a fire brigade is consulted. I have found that some have preferences for a particular method of fire-extinguishing, and what seems to me rather an unreasonable bias against other methods. It would have been helpful, therefore, if the author had given us his views on the relative advantages of various media, but I am glad that the E.R.A. are endeavouring to formulate some guidance in that direction. My view is that there is in most cases a proper application of a particular medium to a particular risk, and I think it would be wrong to say that any certain medium is the correct one to use in general.

I agree with the emphasis which the author places on the necessity for removing the outer hessian coverings of indoor cables. I consider that this should also apply to outdoor cables from the point at which they leave ground level. The value of the outer protective cover largely ceases after the cable has left the ground.

As regards the oil fire-fighting equipment carried by brigades, I agree that it is most important to ascertain exactly what is available. My experience is that it varies considerably in quantity and quality. It should also be borne in mind that if one relies entirely on a fire brigade for protection there is a danger that that brigade may be elsewhere at the time one wants the use of the equipment.

I suggest that breathing apparatus and gas masks form a part of the normal equipment for fire-fighting purposes, because occasions will arise when engineers have to enter a chamber which has been flooded by $CO_2$ or other gas, in order to carry out emergency repairs.

On page 295 the author mentions that the water-spray type of extinguisher possesses a quality which is not common to other types, namely its cooling capacity. While this is a very important point, I should like to say that the foam-making branch pipe possesses this valuable quality, in that it can be used as either a water branch pipe or a foam branch pipe, and can consequently be used on masses of hot metal for cooling-down purposes. Incidentally, the author says that the water-spray installation requires a pressure of upwards of 50 lb. per sq. in., but I am under the impression that at least 100 lb. per sq. in. is necessary for a fixed installation. Hence some sort of supplementary apparatus must be provided to obtain the necessary pressure.

The dislocation of supplies following an oil fire may be far-reaching; there is only one thing to do and that is to hit a fire quickly and hit it hard.

**Mr. R. A. McMahon:** I wish to confine my remarks to one or two points of importance from the fire-extinction point of view.

The author recommends that drainage should be provided for transformer and switch situations to evacuate oil in case of fire, and I do not think that anybody with any experience will disagree. Although this had been done in a case which has come to my notice an adjacent wall had been painted, with the result that, when a fire did occur, the paint melted and, running into the cold drain, froze, thus preventing the evacuation of the oil, which collected and burnt under the transformer, causing it to boil over; thus greatly increasing the fire and the difficulty of extinguishing it.

With regard to the water-spray method of dealing with fires, we are not yet satisfied that it is the best method to employ under all circumstances, nor do we yet know whether it is being employed in the safest manner. An electrical fire, particularly in a transformer, is usually the result of an electrical fault, and it often happens that fire does not break out until the body of the oil has reached a temperature well above the boiling point of water. It can and has been demonstrated that injudicious application of water-spray under these circumstances may result in a boiling action and consequent overflow of large quantities of burning oil, adding a considerable amount of flame and increasing the difficulty of extinction. Investigation is being carried out into this matter, and it is hoped that some reliable technical data may be obtained not only in connection with the use of water but in connection with the technique of fire fighting in electrical installations generally.

Both the author and Mr. Bolton have mentioned the question of co-operation between the engineer and the local fire brigade. I heartily endorse this recommendation, and would go even further. In the case of big towns the necessity may not arise, but in the smaller localities and on the outskirts of large agglomerations, where large

power stations and major substations are by no means uncommon, it is essential that the supply undertaking should ensure that not only will there be co-operation between the local brigade and the engineer, but that the various surrounding brigades, which probably belong to different administrative authorities, will co-operate with each other; as it will often be found that one brigade's equipment is hopelessly inadequate and, unless further help has been catered for by previous standing arrangement, long delays may be incurred in obtaining permission from the chairman of the local-authority's fire-brigade committee to enable them to attend a fire outside their own area.

**Mr. H. Headland** (New Zealand) (*communicated*): The section in which the author deals with the fire protection of generating plant is somewhat disappointing, in that it completely passes over the possibility of a fire starting in the windings of an electrical machine, with disastrous results similar to those shown in Fig. A, which refers to a large vertical waterwheel alternator. The consequences of a fire in a rotating electrical machine are generally accentuated by the draught of air due to the supply of cooling air and the natural draught resulting from the rotation of the machine itself.

Although internal fires in generating machinery are uncommon, the possibility of such an occurrence cannot be overlooked, and for a large and important machine the cost of providing adequate and effective fire protective equipment is very small when compared with the capital cost and economic value of a single generating unit in a major installation. It is also almost negligible even if based on the cost of repairing a damaged winding or the loss of revenue during the time occupied in carrying out the repairs. This can readily be illustrated by a recent example where two 24 000-kVA vertical waterwheel alternators with a capital cost of £40 000 were provided with fire protective equipment at a cost of less than £400 when completely installed. The maintenance cost of suitable equipment is practically negligible, so that as an insurance premium for the safety of the machine the initial investment of 1 per cent of the capital cost of the two machines is well worth while.

The normal systems of generator protection cannot be expected to provide against the consequences of an internal fire in the machine, and the usual methods of dealing with incipient fires are not applicable to generators if serious damage to the windings is to be avoided. For these reasons the use of an inert gas such as carbon dioxide is generally to be preferred. With the installation of a central system of sufficient gas capacity, arrangements can be made for the proper protection of any number of generating units by the use of suitable selection devices. Generally speaking, the requirements of proper fire protection of a generating plant are fairly simple, but in such an installation certain important factors call for consideration.

The system of injecting the inert gas should provide for the prevention of the fire spreading either in the combustible materials of the windings or in the air passages of the cooling system; this condition requires that the air flow and mechanical characteristics of the generator should be given the most careful attention. In vertical waterwheel alternators provision should be made for preventing the gas entering the turbine pit, by means of a suitable fabricated steel liner.

In the case of an electrical fire in a generator it is essential that the flame be extinguished almost instantaneously, and to accomplish this a minimum $CO_2$ concentration of not less than 50 per cent is required within a few seconds of the outbreak. On account of possible leakage in the air ducts the gas discharge should continue throughout the period of deceleration of the machine, which may be quite considerable when the machine has a large flywheel effect. The atmosphere of inert gas

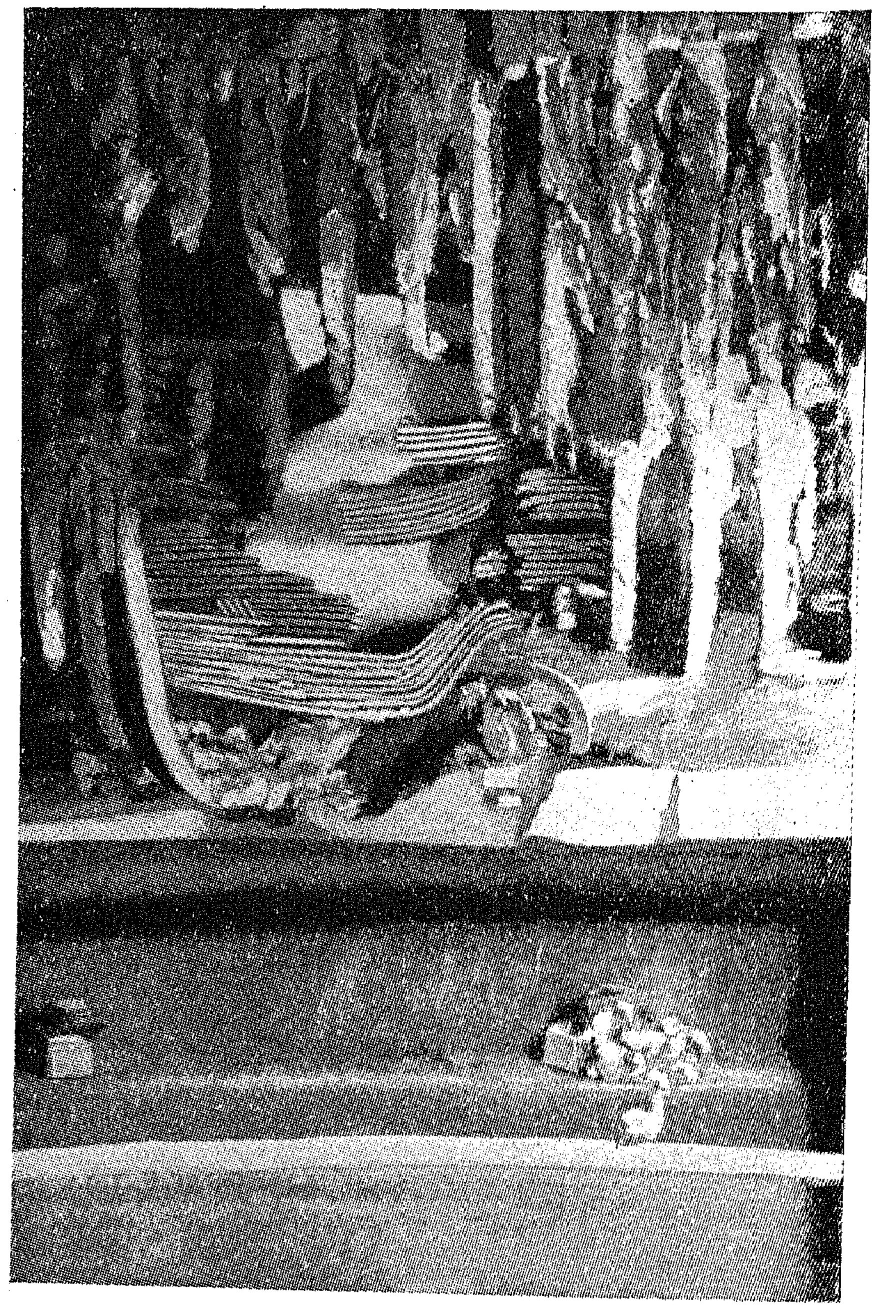

Fig. A

should be maintained for 30 minutes, and a small amount of some strong aromatic compound compressed with the gas so as to render the detection of leakage a simple matter.

The sequence of gas injections into the generator air-circulating system may be divided into three sections, as follows: (i) The first injection consists of a sufficiently large volume of gas at a low pressure which is rapidly discharged to give a high initial gas concentration to extinguish the flame. This is liberated by the operation of a quick-opening valve, and the gas nozzles are so located on the suction side of the ventilating system as

to give the greatest diffusion and concentration of the gas in the minimum possible time. (ii) Simultaneously with the initial discharge the first section of the delayed discharge is released, the volume being approximately the same as that of the initial injection. This is fed into the machine through a series of small orifices and serves to maintain the gas concentration by compensating for leakage in the air ducts. (iii) After a predetermined interval, usually about 20 minutes, the final injection of gas is released and this may have a volume of about one-half of the initial discharge. This operation is carried out by means of a time-delay switch and supplements the original gas until the machine comes to rest. The gas should be discharged above the windings, so that as it settles in the bottom of the pit it passes any burning material which may not have been extinguished by the initial discharge.

The cylinder release valves may be operated either manually or electrically by a system of thermostats, either through a camshaft or by a system of falling weights. It is possible to arrange interlocks with the generator differential protection to clear the generator from the busbars, open the field circuit, trip the turbine throttle valve, and release the gas into the generator ventilating system.

**Mr. W. E. Highfield** (*communicated*): There has been no major disaster to either steam- or water-driven alternators for many years, and in fact the design is so secure and the installation so guarded by automatic devices that open the circuits, cut off the air, and suppress the ventilation, that this apparatus can be *considered secure* "as far as is reasonably possible." There remain transformers and switchgear and their housing.

I believe the large power transformer to be nearly immune from danger from within. Although it is of relatively fragile construction, the enclosed area is so large and the volume of oil so great that a fault to earth does not constitute an explosion. The transformer is not immune from flying fragments, and one can conceive a major accident resulting from an accident commencing in this way. Space, arrangement, and barriers, are the remedy. It must not be forgotten that it is accepted practice to connect across the secondary of the power transformer a small auxiliary transformer, and a short-circuit to earth may cause an explosion in that apparatus which would result in the emission of, say, 100 or 200 gallons of oil on fire, which might well start a major disaster. The tank of these transformers is not made with the same robustness as that of an oil switch, and a welded seam might well open under a severe fault to earth in the windings. Also it is from this transformer that flying fragments are to be feared. Precautions should be taken to get the oil underground, but I feel strongly that the oil must be taken down a good depth or removed to a distance. The flame temperature of burning oil is of the order of 2 000° F., and if the top stones of the soak-away get heated they will act as an admirable wick; the oil underneath will be drawn up and will burn gaily.

The other danger is associated with the switchgear, and this is, and must of necessity be, a much more sensitive point. A disaster to a transformer, main or auxiliary, is not likely to cripple permanently more than one circuit, but a switchgear circuit-breaker may and does involve feeder circuits. I follow the author in placing reliance on a reasonable amount of segregation, without any attempt at a bizarre design. If I may criticize Fig. 4, I should like to see some expedient that avoided bringing the cable to the centre of the switch house. I acknowledge the symmetry of the arrangement and the difficulties of cross connections that it avoids, but since we are discussing difficulties I draw attention to a point of improvement although I cannot suggest the remedy.

With regard to the construction of buildings able to withstand explosions, I believe in a strong floor and a strong roof, with metal-sheathed doors that will blow off and a line of light glass windows fronting the switches. One should beware of trusting to blow-out panels to relieve the pressure. Should an explosion occur it is 10 chances to 1 that the blow-out panels will remain intact and the strong structure will be shattered.

For the rest, it is mostly detail work. Steel must not be considered immune because of the flame temperatures. It must be guarded by concrete or, better still, asbestos. Most woods are not reliable, but jarrah is an easy wood to get and is almost fireproof. Cork itself will burn very freely, but cork fragments can be made into tiles that are fireproof and hard-wearing. Paint I regard as unsuitable. The film is so thin that it can only hold off the flame temperature for a very short time. Fireproofing paint means spoiling the weatherproof qualities of the mixture by boric acid, fusible glass, or alum.

**Mr. L. M. Jockel** (*communicated*): The author's remarks as to the fire-resisting qualities of metalclad gear are interesting and have been amply borne out in practice. A substitute for aluminium is quite practicable, but I should like to ask him whether cast iron is not subject to cracking and consequent escape of compound under sustained heating.

On page 294 he refers to brick walls; these are certainly good from a fire-resistance point of view, and as barrier walls are in my experience preferable to reinforced concrete. The latter material generally develops cracks in time, and should not be used closely adjacent to e.h.t. apparatus. Plain concrete or artificial-stone slabs are satisfactory where phase isolation and barrier walls are employed.

In regard to fire fighting, the use of $CO_2$ as an extinguishing medium has been adopted in at least two important power stations in this country. About 15 years ago, during the discussion of a paper* before The Institution, I suggested the use of this gas, and I believe that only a few weeks ago it was used effectively in a switch-room fire in our largest power station. The efficient use of $CO_2$ of course entails a closed-in space; this can easily be provided for in new plants but not in existing power stations or substations.

Nowadays there is rather too wide a choice of extinguishing systems available for electrical fires, and I am of opinion that closer co-operation is now necessary between supply engineers and fire-brigade officers. Many demonstrations of extinguishing apparatus are conducted on static tanks or other media where the ratio of surface area to volume is not comparable with that of actual apparatus in stations. Further, the seat of the

* J. A. Kuyser: "Protective Apparatus for Turbo-generators," *Journal I.E.E.*, 1922, vol. 60, p. 779.

fire is not always clearly accessible in practice, and there may be actual motion of the combustible material.

On page 296 the author considers explosions and agrees that they have generally been due to gasification of the oil or compound following a failure of the circuit breaker or other apparatus. Such explosions are usually violent, and in two cases which have come under my observation the oil switches cleared the fault but were completely destroyed, and the resulting gas explosion did damage to the building. The first case was a 22-kV substation, where the access door was completely blown off; and the other instance was a 6·6-kV power station, where the switch-room windows were blown into the street.

These experiences naturally incline one to take an interest in the present Continental and American developments of oil-less and de-ion types of breakers for heavy-rupture-capacity circuits, and I look forward with confidence to their use in the near future.

In conclusion, I am glad to note the author's mention of the heating of switch chambers, a point in design which is generally omitted. In addition to the maintenance of a reasonable temperature to prevent condensation, there is the fact to remember that insidious breakdowns of insulation may occur in e.h.t. gear due to expansion and contraction of the busbars and connections. Assuming a design figure of 90 deg. F. is worked to as the maximum temperature variation, it is well to bear in mind that this represents an alteration of about 0·5 in. in a 50-ft. length of copper bar.

**Mr. E. W. Murray** (*communicated*): The author rightly tells us the types of fire-fighting equipment we should have, but he makes no mention of asbestos blankets. These can be of extreme value in the early stages of an electrical fire.

Again, it is no use providing first-aid fire equipment without some training of the station staff in the use of the extinguishing appliances. I should not like to come across another case similar to one I encountered recently where some four extinguishers had been placed near the main entrance door of a store and packing room which had a basement, ground floor, and upper floor. When the question was asked why the appliances had been placed in this position the answer given (in all sincerity) was "so that they would be ready and easy for the firemen in case the brigade was called." Further, the training would enable the staff to be conversant with the apparatus and its capabilities. Unless one has been able to deal with at least a few staged fires one is apt to think that it is possible to see through smoke without getting watery eyes and to breathe smoke without coughing and choking. One is also apt to forget the difficulty of breathing the hot air which may exist inside or just outside a chamber. A few fire trials would very soon demonstrate how much more easily a fire can be controlled if one enters a chamber on all fours. The atmosphere near the floor is clearer, and at this level one can see and avoid falling over obstructions which are not seen when standing, even by a person who may think he is thoroughly conversant with the geography of the chamber. Such training should be given with the help of an expert, perhaps from the local fire brigade, because even with the methods mentioned above there is a risk of gassing if carbon tetrachloride or methyl bromide is used on a fire in a poorly ventilated chamber, unless the fire fighter is wearing a gas mask or breathing apparatus.

**Mr. R. Nelson** (*communicated*): In the Introduction to the paper the author's summary of the situation is well balanced. He justly observes that as technical perfection is neither possible nor economically practicable, the best compromise must be made between reliability and cost. The paper gives the precautions which under present conditions are necessary, but these are, in effect, ways and means of minimizing the possible results of burning *oil*, which results, the author correctly says, "may be of the gravest nature." One general principle to which he considers due regard should be paid in design is the "elimination of combustible matter not inherent to plant"; but when he considers elimination of the only serious offender, namely oil, he is little better than lukewarm where one would expect to find him an enthusiast.

Near the end of the paper there is the clear statement that "On the Continent the development of the oil-less circuit breaker is of considerable interest." He might well have said that, *qua* generating-station and substation fires, it is the best hope in the situation. Later on he makes the curious remark that "Oil-less circuit breakers alone . . . only constitute a reply to a lesser part of the problem." He must surely mean the *greater* part of the problem, for with the disappearance of oil the problem itself disappears. The author is, however, consistent; he is so thorough-going—not to say so conservative—a supporter of oil-filled apparatus, irrespective of the quantity of oil contained therein, that from the fire standpoint he has no good word to say for the small-oil-content circuit breaker. I do not find it convincing to be told that in the event of a mishap, given good drainage, the quantity of oil present is of no great moment. In spite of the author's opinion I would abolish oil if possible, and finally I should like to ask this question: Would the author not recommend that more attention than hitherto be given to the "elimination of combustible matter not inherent to plant?" I am more particularly interested in works substations; many of these from a fire standpoint are full of possibilities which, in the author's language, "may be of the gravest nature." I should have welcomed a clearer challenge to switchgear makers than the paper provides to remove oil altogether.

**Mr. H. Trencham** (*communicated*): The significant point which is made clear by the paper is the extreme importance of switchgear. The extent and complexity of its duties are demonstrated by the fact that there is scarcely any unusual occurrence in an electrical power system which does not occasion in one form or another examination of, or questions concerning the behaviour of, some item of the switching equipment. This condition in itself is quite enough to justify the designer and manufacturer in exercising the utmost caution when making decisions which affect any of the main functions of switchgear.

Mr. Forrest has expressed the opinion that British switchgear manufacturers should examine the subject of oil-less breakers. I can assure him that the subject has been under constant and close examination ever since the E.R.A. demonstrated some years ago the feasibility of using a gas blast for circuit interruptions.

Nobody can question the desirability of removing oil-fire risk from amongst the many which assail circuit breakers and switchgear, but it is incorrect as well as unscientific tacitly to accept the premise that oil fire is the only way, the most important way, or in fact any other than a most unusual way, for a circuit breaker to fail. British manufacturers have felt that, except when oil-fire risk is artificially raised to the position of the dominating issue, oil-less breaker constructions show themselves less satisfactory than oil circuit-breakers in meeting all the requirements of circuit making and breaking. When designers are able to change this condition the oil-less breaker will appear in this country as a matter of course. The immense amount of money spent by manufacturers in proving their products should be taken as an assurance that they are prepared to face whatever cost is imposed in supplying only that which they are satisfied is the best. It would be unfortunate and a loss to the industry if any artificial views or arbitrary actions were to force balanced progress out of its course.

My experience goes to confirm that when an electrical fault occurs there is little, if any, danger of a spread of trouble provided it can be disconnected quickly. If, on the other hand, a heavy fault is maintained on the system for any length of time, major damage is to be expected with the consequent danger of a major shutdown irrespective of whether fire continues after disconnection or not. I am able to confirm from my own experience that good metal enclosure is remarkably effective in allowing a time margin for the action of automatic protective gear, and also in limiting damage when fire does occur.

[The author's reply to this discussion will be published in a later issue of the *Journal*.]

## NORTH-EASTERN CENTRE, AT NEWCASTLE, 8TH FEBRUARY, 1937

**Mr. W. Innes** (Whitley Bay): The author speaks of the comparative rarity of serious fires in main electrical stations; it should be remembered that in recent years with the advent of the national grid system the "power at work" has been increased to a far greater figure than could have been contemplated originally, and unless steps have been taken to get rid of totally inadequate protective gear, fires and explosions will in future be of much more frequent occurrence.

In regard to fire fighting, the first essential is that the affected gear should be made dead immediately, and that plans should be painstakingly prepared to enable this to be done. The seriousness of any fire is enormously increased when the power input to the fault, either directly or by means of what is termed "back-feed," is maintained. It is interesting to recall that in some recent fires the position has been rendered difficult owing to the delay in disconnecting the supply. In the case of the Brimsdown fire (10th September, 1935) the supply was not cut off from the affected area for 30 minutes. The fire brigade had, in fact, to take precautionary measures, such as earthing branch pipes, and the use of high-resistance rubber gloves.* Another example occurred at Portsmouth, where a C.E.B. transformer was on fire. When the brigade arrived flames were leaping 40–50 ft. high, but the brigade was told that it was impossible, locally, to cut off the supply. In this case also the firemen attacked the fire with the gear alive.† It is significant that a well-known London fire officer has recently recommended that high-resistance gloves and footwear should be part of a standard equipment.

On page 295 the author says that he has a slight preference for a fixed installation, and I agree that for any enclosed space a fixed installation is the only possible proposition. Owing to the dense, choking clouds of smoke generated, to approach an oil fire is extremely difficult. I do not think that much cooling can be expected from a high-pressure water-spray system. As a matter of fact, very little water is used by this method, even on a large fire. The author does not say a great deal on the question of fire resulting from lubricating oil, although such a fire may be a far greater menace than a switch or transformer fire. Should an oil pipe fracture and the escaping oil come in contact with hot surfaces, the intensity and rapidity with which the resulting fire is propagated is nothing short of alarming.

It is not beyond the bounds of possibility, in the event of failure of any of the high-pressure oil piping associated with the governor gear, to arrange for the whole of the oil being delivered by the high-pressure oil pumps to be bypassed directly into the reservoir in such a manner as to evacuate the whole of this high-pressure system external to the reservoir. Such an arrangement involves no risk to the safety of the machine, but could not be applied to the lubricating system, for obvious reasons.

While there have not been a large number of major fires (5 in the past 10 or 11 years), this potential danger is always with us. In four of the five stations where fires have occurred disaster has arisen from oil escaping from low-pressure systems and not from the high-pressure relay system as one might have imagined.

To install a fixed fire protection system to cover all the risks in an engine room is wellnigh impossible, owing to the complex system of steam and oil piping. I understand that an endeavour has been made to overcome this difficulty by installing high-pressure water sprays in the turbine lubricating tanks. Has the author any information regarding this point?

It may be that, in future, steps will be taken to remove the main oil tanks and pumps from the steam end of turbo-generators. There seems to be no practical difficulty in doing this, but it is not at all certain that were this done the risk would be eliminated.

I am in agreement with the author's remarks regarding explosions. In the main, damage to structures has been caused by slow gas collection in the building. Is it not possible to install a gas detector? By this I do not mean a smoke detector, such as that now in common use. This could be arranged to operate the usual alarm circuits in an attended building, or in an unattended building could be arranged to increase the ventilation

* Annual Report of the Institution of Fire Engineers, 1936, p. 33.
† *Ibid.*, 1936, p. 39.

and so prevent an explosion. There are many substations where it would be an advantage to install a gas detector, and there appears to be no practical difficulty about doing this.

I am quite sure that the doubts regarding busbar protection will gradually disappear, and it will be accepted practice in the future. The protective apparatus for this purpose has recently been extensively developed, and is installed or in process of being installed in a number of large stations.

**Mr. H. W. Clothier:** The author does well to remind us that we "must not be stampeded by single exceptional occurrences." It is comforting to be told that temporary interruptions of half an hour are permissible.

He also says that "sound physical layout is even more important than sound plant." May this be taken as an easement in the extent of the alterations that are essential when considering existing plant? The physical layout recommended includes dividing plant into fire sections, but in the light of knowledge gained from testing-station performance it may be necessary, with some of the old plant, to adopt further electrical sectionalizing or modified system layouts also, in order to reduce the maximum possible vicinity short-circuits to the safe limits of the plant. When reviewing existing installations, and considering the rarity of a circuit breaker ever being called upon to deal with the maximum vicinity short-circuit, given approved physical layout, would the author be prepared to adopt an easier standard in assessing the safe limits of breaking capacity?

Notwithstanding that the number of circuit-breaker failures has been so small in comparison with the vast numbers of circuit breakers in use, some notice must be taken of them, bearing in mind that faults may in future become more onerous and numerous. Even one failure starts a search for preventive measures, if not for existing plant, at least for the designs of the future. In the long run this urge for technical perfection must serve to effect economy. For example, in one of the most serious fires the major delay in restarting was due to renewing all the cables in the basement. On existing equipment, where it may be impossible to sectionalize existing cable basements, it may yet be possible to divide these into draughtproof partitions. Again, the same fire, having destroyed a whole set of control cables, may lead in due course to the use of a multi-core control cable that will not burn.

Constructional developments beyond a certain stage point to the need for reduction of working currents by the adoption of higher system voltages so as to avoid those heavy currents that bring a train of difficulties.

Although much regard must be paid to the correlation of past satisfactory service conditions of circuit breakers with modern ratings on new standards, it is probably more important to give attention to the insulation, because, as the author says, "insulation failure is the most important consideration of all." Recent insulation has been much improved, but old insulation is not likely to improve with time, particularly if subject to uncontrolled voltage surges, as it is, for example, from overhead lines. The avoidance of this type of stress on the insulation is a matter for development.

Sustained arcing of any kind, whether within a circuit breaker or on open conductors, even where no oil is involved, may give rise to explosions. This risk may be best allayed by high-speed isolation of all faults. It may be that "protective gear cannot prevent failures, and may produce them," but it does constitute the safeguard against extension of local damage, and, when properly designed, will be no more suspected of producing failure than the other unit protective systems that now cover all links except the busbar zone. It may even assist in preventing one arcing fault from setting up others, an effect which not infrequently occurs.

With regard to site testing, the Doble system appeals to me as a progressive method of planning and observation that should be of great value in maintenance work where certain insulation may be subject to deterioration. (Here Mr. Clothier read some quotations from American and Canadian publications about the working experience of busbar-zone protection, and in contrast a letter about routine on power-station fire-fighting in another oversea district. He also referred to recent pebble protection tests made at Hebburn.)

In conclusion, metalclad construction, which the author claims has contributed to safety of operators, reliability of supply, reduction of costs, and limitation of spread of fire, was introduced at a time of troubles with fires, shocks, blowing-out isolation switches, spreading arcs, and so on. Notwithstanding its steady progress over the last 30 years, there is still scope for thought on further technical perfection arising from "single exceptional occurrences."

**Mr. R. W. L. Harris:** The extent to which provisions to reduce the spread of fire and the consequential damage within a fire section are applied at any station must, as the author points out, depend on economic as well as technical considerations. If a modern station has correct physical and electrical sectionalizing, as well as protection in all zones to obviate the possibility of sustained arcing, this represents a big advance in design, and furthermore, if the individual fire sections are protected by permanent and local fire-extinguishing plant, it is reasonable to assume that any possible outbreak will be of short duration, say 5 or at the most 10 minutes. Any subsidiary precautions may then be designed with a view to affording protection against a fire of this duration. A series of fire tests each lasting from 10 to 15 minutes has been conducted to ascertain, amongst other things, the relative merits of various means of protecting the short lengths of cable between the glands of switchgear dividing-boxes and the floor. The protective arrangement and floor seal shown in Fig. B was found to be very effective, and is included here because it is comparable with the arrangement shown in Fig. 2 of the paper.

The tests further indicated that for the fire protection of cables laid in trenches the use of pebbles of between ½-in. and 2-in. mesh as a filling medium is very effective, especially if the pebble bed is adequately drained. The lead on cables only 4 in. below the pebble surface of such a bed, with a fierce oil fire burning on the surface, was found to be only slightly warm after a considerable period, and as soon as drainage was allowed to take place the fire was extinguished in a few seconds. Because

of the ready drainage they afford, pebbles appear to be much superior to sand, screened ballast, or granite chippings, for this service.

I am in agreement with the author that $CO_2$ and methyl bromide are the most suitable fire-extinguishers for use with indoor switchgear where it is important that the insulation of the gear should not be impaired, and of these two I prefer $CO_2$. For transformers and cable basements, I think the high-pressure water spray has much to recommend it.

There is one small point I should like to raise in connection with Fig. 4 of the paper. It is stated in the text that this shows sectioning as applied to indoor 66-kV switchgear; but the illustrations seem to indicate a situation with the circuit breakers themselves partially out of doors.

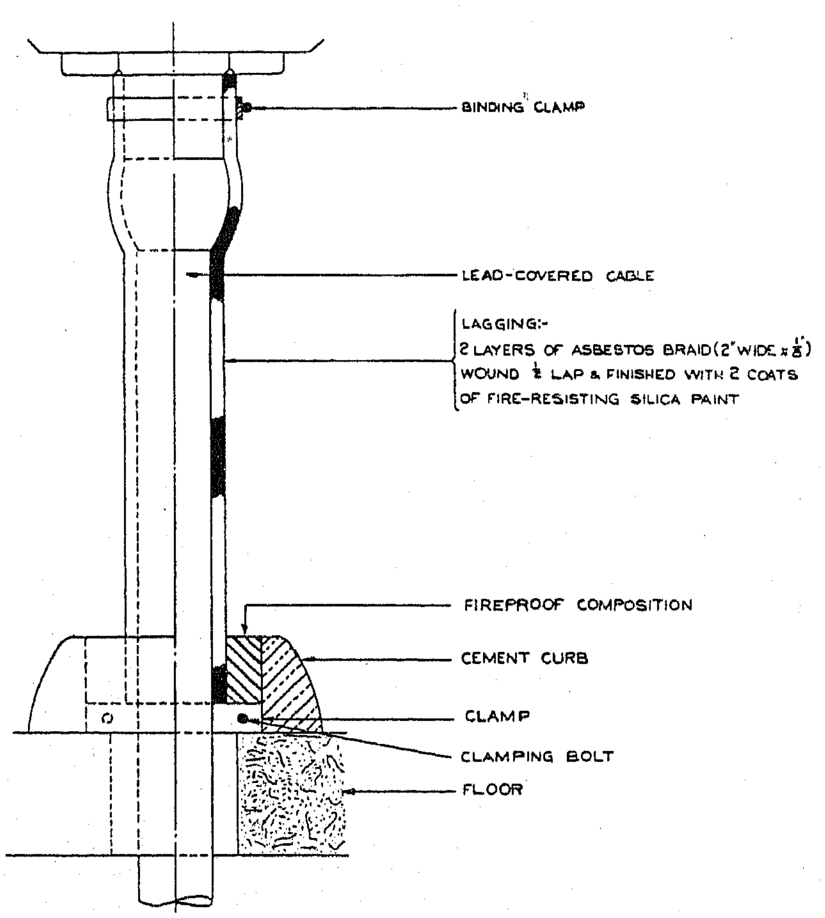


**Fig. B.**—Half sectional elevation showing fire protection of short lengths of cable between dividing-box gland and floor seal.

**Mr. H. Hoyle:** Whilst it is agreed that fires in any one power station do not occur frequently, it cannot be denied that the risk is always present. The results are serious; as continuity of supply is of paramount importance, the problem of fire protection must be given the fullest consideration.

On economical grounds complete duplication of all equipment is an unreasonable precaution; we can only proceed so far in this direction, and the next step is to install fire-extinguishing equipment of such a type that the fire can be dealt with rapidly and effectively. To accomplish this satisfactorily and with the minimum danger to personnel, installations of the fixed type are essential.

With regard to the extinguishing of oil fires by means of water, it should be noted that water from branch pipes of the usual pattern must never be discharged on to an oil fire as the tendency is to spread the area of conflagration and not subdue it. With the high-pressure spray system to which the author refers, water is applied in such a manner that it forms with the oil a mixture or emulsion which will not burn. The water discharged from the nozzles issues in broken streams which are not conductive. It is now generally known that the Central Electricity Board make use of water in broken streams for washing the 132-kV insulators at several stations.

Regarding the fire risk with generating plant, it does not appear to be generally known that the usual grade of lubricating oil used will spontaneously ignite if it falls on to an exposed surface such as a steam pipe or valve chest at a temperature as low as 560° F. Ignition results from a "cracking" process, with the formation of new substances. The lighter fractions volatilize, and exothermic reactions take place with the oxygen of the atmosphere. Aldehydes, acetic acid, and bituminous matter are formed, and oil having an original open flash point of 400° F. produces fractions with a flash point as low as 175° F. Thus if escaping oil from a pipeline comes into contact with a hot steam pipe ignition can result, with disastrous consequences. With a pipeline under pressure the oil can escape in the form of a spray and its ignition results in a very serious conflagration, the oil spray burning with intense heat. A high-pressure water spray will extinquish such a fire almost instantaneously, owing to emulsification taking place.

I am a strong advocate of automatic protection, as this avoids any delay in bringing the protective equipment into operation. Delays of a few seconds are of the greatest importance in connection with oil fires, which spread with amazing rapidity.

**Mr. R. Willoughby:** From the user's point of view I should like to urge manufacturers and those responsible for the layout of stations to pay a little more attention to reducing the fire risks associated with small items of equipment. Small pieces of apparatus, such as current transformers, voltage transformers, and small auxiliary transformers, connected to the main power circuits, are the weakest link in the chain of a modern station layout, and yet in order to save a few feet of copperwork these items are often mounted high up in such positions that, in case of fire, burning oil may be spilled over major apparatus. Although the quantity of oil involved may be small, if this is alight and allowed to run in amongst the cooling fins of a large transformer, or beneath a switch tank, the results may well prove disastrous, particularly in an unattended station. In an existing installation it is not always practicable to remove the offending small gear to a safe distance, and in such cases screens should be provided to direct any spilled oil away from major gear, and into a suitable soak-away.

Another fault of design frequently met with on outdoor-type transformers is the placing of small oil pipes, for air relief or for supply of oil to terminal bushings, in such a position that they virtually act as arcing horns! I have actually come across cases where these have been burned through by a flashover from an e.h.t. bushing, and oil from the conservator has flowed all over the main transformer. When (if ever) these little pipes are necessary they should be electrically screened

by an iron strip having a sufficient section to withstand a flashover power arc, bearing in mind that a flashover by no means always takes the geometrically shortest path to earth.

With regard to extinguishing apparatus, I should like to emphasize the necessity of providing an adequate reserve of the extinguishing medium used.

Fire, once started, has a nasty habit of lurking in crannies, and if any smouldering is overlooked it may easily bring a recurrence of the conflagration. It must be indeed mortifying, after having to all intents and purposes overcome a serious fire, to find it rekindled when one has practically exhausted the charge in an expensive fire-fighting equipment. This, I feel, is one good argument in favour of a high-pressure water-spray or a saponified-foam installation, worked from town water mains, whenever the latter give a sufficient flow and pressure.

**Mr. H. Leyburn:** I have no comment to make on the sections of the paper dealing with the physical arrangement of the plant thought to be desirable for limiting the damage due to a fire. In my opinion, however, greater emphasis should have been laid upon the prevention of fire than upon the limitation of damage once a fire has started.

Although the author states on page 290 that "rapid isolation of a fault is an important factor in reducing the risk of development of fire, and hence sound quick-acting protection is necessary," if one may judge by what he says about busbar protection he is rather lukewarm about the application of this principle to busbar zones. It is important to realize that, although the physical separation advocated by the author may go a long way towards preventing the spread of a fire from one section of a power station to another, the healthy sections remain vulnerable so long as the electrical interconnections between them and the section on which a fault persists are not interrupted. I contend that the only way of achieving this electrical segregation is by some form of busbar-zone protection, which must usually be of the unit type in power stations, but may be of the back-up type in substations. In the absence of means for rapidly isolating the faulty section there is a risk of sympathetic faults not only in other sections in the same power station but also in units of the supply system which are widely separated geographically. In this connection it is necessary to visualize what happens on the occurrence of a fault in an unprotected zone, e.g. a busbar zone. The fault, which can be assumed to be an earth fault, gives rise to a current usually limited by the earthing resistance to, say, 1 000 to 2 000 amperes, and the attendant is advised of the breakdown by the ringing of an alarm bell. Unless busbar protection is fitted there are now two ways of dealing with the breakdown, namely either by allowing the fault current to flow and relying upon the attendant to clear the faulty section manually, or alternatively by disconnecting the earthing resistance automatically, thus reducing the fault current to a value corresponding to the charging current of the network, and, as before, relying upon the attendant to clear the faulty section.

I consider that since faulty sections cannot be expected to be located and cleared manually in less than, say, 1–5 minutes, the first alternative cannot be adopted with present-day equipment, because the earthing resistance would be burnt out during that time; and although on the face of it the second alternative may look safer it has other serious disadvantages, namely that it may bring about a risk of sympathetic faults in other parts of the network caused by oscillations set up by the earth fault on the now insulated network. I should like to know which of the above two alternatives the author prefers.

Although in my opinion the best way of dealing with a busbar-zone fault is to disconnect it automatically as quickly as possible, and thus avoid the possibility of its causing other faults on the network, I sympathize with the author's hesitation to adopt such a departure from present-day practice. I would suggest, therefore, that as a compromise the discriminative busbar-zone protective gear should only prepare the trip circuits of the circuit breakers controlling a faulty section, and the final tripping should be left to the attendant, who need not now waste time in locating the faulty section. In this way the faulty section could be disconnected discriminatively with reasonable speed, and at the same time the safeguards required by the author against inadvertent operation would be provided.

There are a number of less important points I should like to discuss briefly. The author states that "one serious difficulty lies in guaranteeing that the remote end of connected feeders shall be cleared when a busbar fault occurs, as otherwise only 50 per cent of busbar faults are provided against." I can assure him that there is usually little difficulty in meeting this requirement. Again, the author states that "protective gear cannot prevent failures, and may produce them," and from the context it appears that by "failures" he means "failures of supply." I do not agree with this statement, because the primary object of protective gear is the prevention of failure of supply, and this holds good irrespective of whether it is protecting busbars or feeders or any other plant. In conclusion, I would suggest that if either fully automatic or semi-automatic busbar-zone protection is adopted, means provided for dealing with fires after they have started will be brought into action much less frequently, since the fundamental cause of fires, namely sustained arcing, will be almost entirely eliminated.

[The author's reply to this discussion will be published in a later issue of the *Journal*.]

## NORTH MIDLAND CENTRE, AT LEEDS, 16TH FEBRUARY, 1937

**Mr. W. Dundas:** It is an undeniable fact that an alarm of fire arouses more fear in the heart of mankind than anything else, and such an event at an electricity supply station is no exception.

Fortunately, serious fires in power stations and major substations are comparatively few and major disasters through fire are rare; this probably accounts for the somewhat limited attention given to the subject in the past. Modern stations are probably more vulnerable to fire than those built years ago, principally owing to the greater

concentration of power and the presence of large quantities of oil in switchgear and transformers. At the same time it is true to say that improvements made in the design and construction of equipment have had a counteracting effect. In view of the possibility of widespread dislocation of the many vital services depending upon the supply as a result of a serious fire, it becomes essential to take due precautions against such an eventuality.

The author suggests that failure of insulation is the cause of fire, and generally speaking this is true; but there are other factors, such as the failure of a switch to clear a fault, and damage to cable sheaths due to heavy earth currents, the latter calling for careful attention to efficient bonding and earthing. The presence of oil and the attendant possibilities of explosion are a greater danger, and present a difficult problem when the design of the switch house is being decided upon, especially when consideration is given to protecting against air raids; for the fulfilment of the one set of conditions is diametrically opposed to the fulfilment of the other. Again, explosions appear to be directional, and the direction cannot be determined beforehand. The only precaution that can be taken is to relieve the pressure set up within the building as far as possible by providing suitable vents in the shape of hinged shutters in the walls. This measure introduces another objection, by affording an outlet for the $CO_2$ gas which may be used for protection against fire, especially if the fire gains a hold. The solution to the problem therefore appears to be to limit the duration of a power arc by means of suitable protective gear, and to provide windows in the building about 2 ft. above the top of the switchgear, relying on inert gas to quell any fire that may occur.

The risk of explosion and increased fire hazard raises the question of oil-less switchgear, which has been developed to a large extent on the Continent, and it seems to be quite within the bounds of possibility that that type of gear will be developed eventually by manufacturers in this country. It is of interest to note, however, that a consensus of opinion recently obtained from operating engineers in America indicated a unanimous verdict in favour of the oil switch, and no departure from the present practice was recommended.

I entirely agree with the author's recommendations as to the type of fire-fighting equipment to be used for switchgear and transformers, and would exclude the use of water where there is any possibility of it coming into contact with insulation and oil. Unfortunately, gas possesses poor cooling properties, and it may be necessary to bring a more effective cooling medium to play on the damaged portion which may have become overheated. If water is used with care its damaging effect can be confined to the portion of the gear already affected.

Automatically-controlled fire protection is essential on the score of rapidity of coming into action, and more particularly owing to the impossibility of personnel entering the building on account of the dense smoke associated with burning oil and bitumen.

The protection of turbine lubricating systems does not appear to commend itself to many engineers, but it is of some importance, and the difficulty generally is in determining the expenditure justifiable on fire-fighting equipment, taking into account the risk.

**Mr. G. P. Henzell:** In a large generating station I should like to see at least three or four sections. It may be that in future stations with big generators we shall couple one generator to each section, connecting the sections together by reactors, section switches, etc., so arranged that in the event of one section being destroyed that section is simply cut out and the outside supply brought into use to replace it until repairs have been effected.

I have had some experience of switchgear and large-transformer fires, and have been struck by the incredible rapidity with which the fire develops. In a few seconds it may assume such proportions that no hand equipment will deal with it.

Has the author had experience of automatic fire apparatus coming into operation during an actual fire in a station or substation? In demonstrations of such apparatus it is generally arranged that the burning oil is confined, although in practice this condition may not obtain.

I should like to mention the possibility of a fire in the engine room due to the ignition of the turbine oil. Such fires have occurred on rare occasions, and can prove very serious. I have seen lately some turbines in which all the oil pipes are encased in an outer sheath of tubing. I do not think that such drastic measures are necessary: much can be done by installing oil pipes of solid drawn tubing and avoiding unnecessary small unions, cocks, and small piping. If these points are given attention, the risk of a turbine fire is very small indeed.

**Mr. R. M. Longman:** Fires in power stations may be caused by the failure of an oil switch, by the bursting of its tank, or by the failure of insulation at some point. The first is a very real danger owing to the large amount of oil switchgear of doubtful rupturing capacity still remaining on systems which have grown rapidly. In many cases the tanks are too weak, and are not properly secured to the top plate. The oil vents should be connected as directly as possible to the outside of the building. The failure of the main cables is another possible source of trouble, but, if these are laid and connected in a suitable manner to the switchgear, fire from such a cause should not arise. Faults and the resultant fault and earth currents have been and still may be the cause of fire and damage, particularly on the secondary wiring. A further point is that the layout of the cable basements is as important as that of the switch room, particularly since a fire in the basement may not be noticed until some time after it has started. Metalclad switchgear having two sets of busbars should have them separated by a fireproof partition.

In considering protection against fire the question arises as to how much expenditure can legitimately be incurred. Considerable attention to this point is justified in the case of power stations or substations controlling large amounts of power.

The success of fire-fighting depends first on the quickness with which the fire-extinguishing apparatus can be brought into play, and secondly on the facility of applying the apparatus to the source of the fire.

**Mr. W. A. A. Burgess:** The major cause of fire in electrical switchgear installations is insulation breakdown. Neither porcelain nor any of the fibrous forms of

insulation can be regarded as entirely immune from breakdown, porcelain because of its lack of homogeneity and liability to crack and splinter, and the fibrous forms owing to the human element in manufacture and to carbonization with excess temperature.

Mr. Dundas would have us consider the use of Continental designs of oil-less circuit-breakers. These rely more upon solid insulation than any other form, and their fundamental design necessitates the use of the least satisfactory forms of insulation. In any form of insulation without oil immersion, the fire risk is always present, and incipient breakdown almost inevitably becomes a major occurrence which cannot be stopped or retarded. The immersion of insulation in oil provides the insulation with a seal against atmospheric moisture and from contamination, and retards, if it does not entirely prevent, a breakdown due to incipient defects. I maintain, therefore, that in spite of its inflammability, which has been very much overstressed, oil immersion is the only efficient means of maintaining high-voltage circuit insulation.

The oil-less circuit-breaker has still further limitations. The air-blast circuit-breaker has given an excellent performance on test, but consistent results are most difficult to maintain. When in perfect condition this type of circuit breaker clears the circuit in half a cycle quite consistently. If it does not clear in half a cycle, however, the general experience is that it will not clear at all, since its operation depends entirely upon both an optimum throat passage and an adequate air blast. This type of circuit breaker is also affected by the presence of very small quantities of oil and other extraneous substances; in fact, my experience is that it requires only a mere smear of oil on the contacts to prolong the arc beyond the critical half-cycle, and prevent the clearance of the circuit.

The alternative form of oil-less circuit-breaker available from Continental sources is the expansion type utilizing water vapour for de-ionizing the arc. Water, when properly handled, is a very good arc cooler and quencher, but is most undesirable in the proximity of insulation. It would also appear from test results that expansion circuit-breakers have very small margins. They behave reasonably well within or below the maker's rating; after that, anything may happen. For closing duty, preconductivity of the water requires high operating speed, otherwise trouble may be experienced.

It will be noted also that the Continental designs abandon the use of water in the expansion-type circuit-breakers over a certain size, and for the larger sizes rely upon a small volume of oil used in the same way as the water, which savours very much of starting a fire on the top of an open oil vessel and letting it burn.

I think most of us agree that if we could safely reduce the oil volume in a circuit breaker, we should do it; but that it is unwise to offer to electrical supply authorities paper designs unbacked by exhaustive tests. We are all trying to arrive at a reduction in oil volume but we will not put anything on the market which is not safe.

The author's objection to busbar-zone fault protection can only be due to a fear of inadvertent tripping. An inadvertent operation of unit circuit protection is liable to cause inconvenience, but inadvertent operation of busbar-zone protection might be regarded as a catastrophe. Various manufacturers have given the subject careful attention and are prepared to offer reliable schemes.

I prefer pebbles to other forms of filling for oil drainage. The author will probably agree that sand is not only less readily drained of oil but may also constitute an undesirable heat insulation if used to cover cables over any appreciable length under conditions which allow it to remain dry. The other forms of filling, such as rough rubble, brick, etc., are not suitable because they present more oil-holding surface, which is undesirable, and they do not cool the oil so quickly.

It may be of interest to refer to the results obtained in a recent test of various methods of protecting cables and switchgear from the effects of oil fires. A switch oil fire was started with petrol and allowed to burn for 10 minutes, during which it reached alarming proportions. At the end of this period the fire was quenched by the Mulsifyre system, and the protection afforded by various cable coverings was noted. In the case of cable wrapped with asbestos tape and silica-painted, the cable was found to be only just warm, and there was no damage to either lead or paper. A split asbestos cement tube afforded a similar measure of protection. Having in mind the great intensity of the fire created, and the ameliorating conditions due to pebble drainage, busbar-zone fault protection, and efficient fire-fighting equipment, with which I am sure all future major installations will be provided, I think the results of this test will be comparable with those of a fire of a longer period, at least as regards the panels not directly involved in the original breakdown. The test also demonstrated the efficiency of pebble drainage: blazing oil tipped on to a pebble bed was quickly quenched, and much quicker than on a similar bed of granite chips. A lesser measure of quenching was afforded by iron gratings. Finally, the main body of the oil in the tank (which by then must have been very warm) was found—when tipped on to a concrete floor on which a layer of oil was burning—to be sufficient to put the fire out.

The Mulsifyre system is the quickest fire-extinguishing means I have ever seen. I should have no hesitation in installing it to deal with a transformer or with any similar case where the fire could only involve a single item which would be so damaged by having caught fire as to require re-winding in any case. I should hesitate to install it to protect switchgear where the insulation was largely of a fibrous nature, and where dampness persisting long after the fire has been extinguished forms an objection almost as great as the fire itself.

Regarding the subdivision of control panels, I have seen several instances of recently-installed control cubicles with no panel barriers whatsoever. I have always considered it necessary to provide a division or barrier at every panel in a control board of cubicle form. Fires do occur on control circuits, and means should be taken to prevent the fire from spreading beyond the cubicle in which it originated, since the destruction of control or other secondary wiring cripples the panels concerned for a prolonged period.

In conclusion, I should like to ask the author whether he has any direct evidence of toxic qualities associated with either methyl bromide or carbon tetrachloride. I should expect methyl bromide to be the worse in this

respect, but I do not think there is much risk to life associated with either, and I would not hesitate to use either in a confined space.

In my opinion $CO_2$ is the best possible means of fighting electrical-switchgear fires, and I think it should be accompanied by pebble drainage, protected cables, busbar-zone fault protection or indication of the simplest reliable form, and a reasonable amount of subdivision.

**Mr. D. P. Sayers:** Mr. Burgess has emphasized the drawbacks but underrated the possibilities of the oil-less breaker. This type of equipment has been much more widely adopted on the Continent than in this country, mainly because the authorities abroad have had to give more attention to the matter of air raid precautions. Granted that the oil-immersed breaker is reliable and breakdowns are rare there is, nevertheless, the risk of the oil getting on fire, and the real danger lies in the possible damage resulting from an oil fire. I hope that British manufacturers will not take up the attitude that because the oil-less breaker possesses certain defects at the present stage it is not worthy of further consideration. It is to be hoped that they will not lag behind Continental manufacturers in research and development work which may find a way round the difficulties and eventually produce a thoroughly satisfactory oil-less unit.

It has been suggested that many fires originate through insulation failure. In most of our present forms of oil-immersed circuit-breakers the presence of oil in the switch tank does not protect the busbar insulators. The busbar insulation is left exposed to the air, and so oil-immersed gear is no better off than oil-less gear in regard to busbar-insulation failures. A great many substations have not been laid out to permit of routine testing of busbar insulation. There is usually only one common busbar, although there may be alternative feeders and transformers. A transformer can be taken out of service and tested occasionally, but in practice it is inconvenient if not impossible to make the busbar " dead " for testing the insulation. I suggest that switchgear manufacturers will have to consider how facilities for routine testing of ordinary substation switchgear can be improved.

We have quite a number of large transformers in Sheffield and we have made a practice of keeping the coolers separate from the transformer tank. Most of the coolers are of " A " type construction. I should like to have the author's opinion about providing a wall between the tank and the transformer. Does he consider there is a risk of fire spreading from the transformer to the cooler, and would a wall stop it?

In much of the metalclad gear produced in the past it has been fairly general practice to use open-type fabricated frames. I suggest that the frames ought to be filled in with sheet metal on one side and at the back, so as to provide a barrier between panels to prevent fire spreading from one panel to the cables of another panel.

In one of the author's slides showing a large substation the transformers appeared to be placed indoors. This is contrary to the modern practice of putting all large transformers outside the substation building.

**Mr. W. J. Howard:** While I support the use of sand for oil-drainage purposes I suggest that instead of gravel and rubble one should use seashore pebbles. These provide a smooth surface and fairly large cavities over which the oil can run and rapidly cool; rubble and sand, on the other hand, present obstacles which act as wicks to the flaming oil.

I should like to refer to an experience I had during some fire tests in 1918. An attempt was made to start a fire by igniting 2 gallons of petrol in a large tank containing 80 gallons of oil, but the whole of the petrol burned out and we still had no fire. At my suggestion the tank was then lifted off the floor, the oil was brought to boiling point by burning timber beneath the tank, and a bucketful of water was poured in. At once an enormous flame shot up.

Danger of fire may arise from the pear-shaped trifurcating box which is often fixed on the side of a large transformer. With a box of this shape the insulators and outlets are only 2–3 in. from the top, and the space below, about 18 in. deep, is filled with compound. In the filling of these boxes a shrinkage will always take place, depending on the temperature at which the compound is poured in and on the class of cable which is used. The shrinkage is often such that the insulator is left bare, or nearly bare. Under fault conditions this point is ideal for a flashover. If the boxes were designed so that they had 6–8 in. of compound on the top of the insulators, such flashovers would not occur.

If large single cables that are connected to a transformer are not properly guarded, a magnetic force is set up that will break them away. Arcing may then occur under conditions which are ideal from the point of view of creating a fire. A method that I have used in substations rather than the ordinary cable racks attached to the walls is to build inside, at the back of the face of the wall, concrete shelves on which the cables are dropped in. Cables installed in this way are in a cold position, and there is no risk of fire touching them.

Turning to the question of busbar-zone protection, one of the systems put forward by the author is a modified form of the arrangement I have had in use for 20 years, namely the leakage-to-frame system. We have used this to protect rotary convertors and static transformers, and have employed a setting of about 25 amperes. To make this arrangement foolproof for busbar-zone protection, a second current transformer is put on the neutral of the main transformer and so arranged that a fault current must flow through the neutral as well as in the earth from frame to operate two relays before the circuit is tripped. This device obviates tripping due to stray currents. Our earthing system is similar to that employed on the grid. It is so designed that every earth-fault current of 10–15 amperes or more rings a bell; if we find that a transformer has tripped and the leakage relay is down, all we need to do is to ring the station to ask whether the earth bell has rung. If it has, there is almost certainly a fault in the transformer.

A fault can occur quite a number of times on a cable or in a transformer before the circuit is tripped. I have known a feeder to remain in circuit under fault conditions for a fortnight before it has actually broken down. My contention is that if the system I have described were used more widely the faults would be cleared before they gave rise to fires.

Danger of fire may arise from the use of the ordinary-type lug sweated on to the cable core. If such a lug is

called upon to deal with a large current, there is the risk of the solder melting and the cable falling away. I use a modified lug, bored from the top with a taper hole. After putting the cable into position, I drive a tapered cone into the core under the outer layer of strands in such a way that the core is mechanically wedged in the lug. The strands are thus displaced, and one has better facilities for soldering. The cable will still hold and make contact even if it gets red hot, as the angle of the cone is such that it will hold it in position.

**Mr. G. W. Jenkins:** Has the author had any experience of fires arising from rotating machinery? The point is of interest in view of the inflammable gases formed from the volatile constituents of insulating varnishes in enclosed machines. I have had experience of opening up a new, totally-enclosed slip-ring motor after a run. A nearby light immediately caused an explosion and a fire about the slip-rings. There is a possibility of the air in the enclosed air cooling circuits of turbo-alternators becoming mixed with gases given off by the insulating varnish when the machines are warm, and particularly when they are new. The mixture may be somewhat inflammable. I believe research is now being carried out to investigate the inflammatory nature of gas given off by insulating varnishes when warm.

**Mr. J. R. Rylands:** May I say a word of warning with regard to the use of carbon tetrachloride for extinguishing fires? A whiff of hot carbon-tetrachloride can be very unpleasant and may produce violent sickness, though I do not know of any fatal cases. Regulations were issued some time ago governing the use of this liquid in, I believe, the dry-cleaning industry. Carbon tetrachloride is a powerful solvent, and attacks almost every material of construction used in electrical engineering. If used on a fire in a transformer, it would probably render the transformer as useless as if the fire had been left alone. My experience of carbon tetrachloride is that it should only be applied as a last resort, and even then only by persons experienced in its use.

**Mr. W. Fordham Cooper:** There are a few points of detail in the paper with which I do not agree. For example, the author states that floor drainage to remove oil quickly is among the provisions which is not essential but desirable. From my own experience, I should have placed this in the category of provisions which ought always to be made in major electrical stations. Again, although I am ready to agree with him that a serious fire is a rare occurrence, the dislocation of supply which sometimes results from even a small fire may cover such a wide area that the effective frequency of trouble is very much higher than would be indicated by dividing the number of fires by the number of important stations, and this, I think, again applies to the problem of busbar-zone protection. At the present moment very rapid advances are being made in this direction. I would point out that not only dislocation of supply but actual damage may occur at points remote from the station in which a busbar-zone fault occurs. For example, on one occasion a fault to earth on one phase at one station was limited to a comparatively small figure by the earthing reactor at an adjacent station where the system was earthed. The fault occurred in the unprotected zone of the busbars, and it was therefore not cleared automatically by any of the selective protection between the stations or at the remote station. As there were several sources of supply in parallel, the fault currents were not at any point sufficient to operate any of the breakers on overload. They were tripped by hand after 1–2 minutes. Had the fault occurred in an unattended station it might have continued indefinitely. As a result, the earthing reactors were seriously damaged and the stray currents in the earth did considerable damage to pilot cables.

There are four ways of stopping an oil fire, namely (1) remove the oxygen from the oil, or (2) remove the supply of oil from the fire, or (3) cool the fire below the ignition temperature, or (4) so dilute the oxygen that it can no longer support combustion. The removal or exclusion of the oxygen is usually effected by a foam blanket. Its dilution is effected by the introduction of

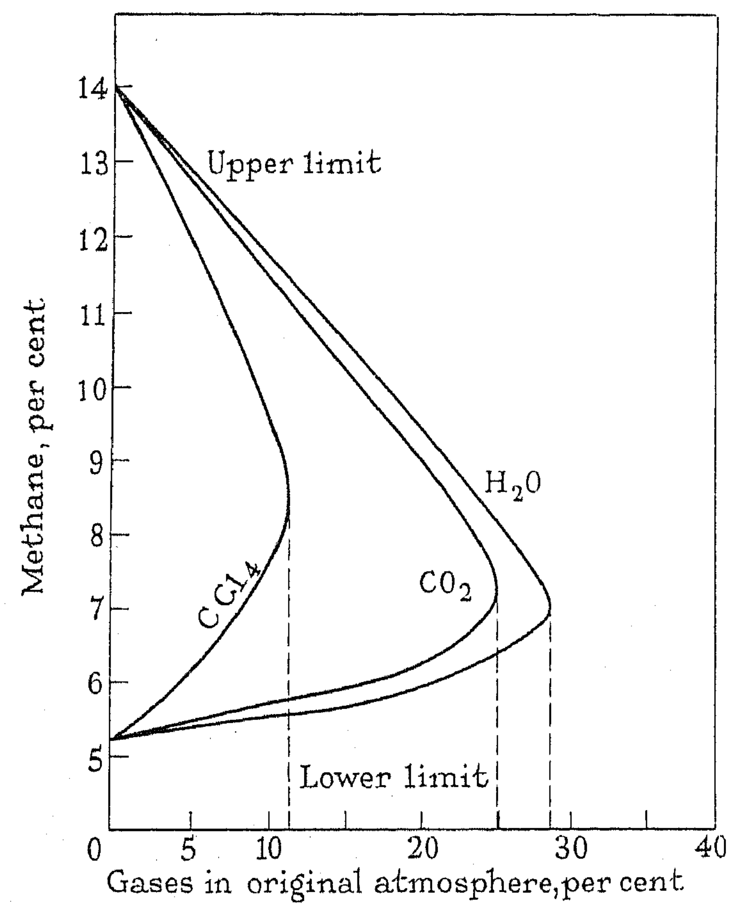


**Fig. C.**—Limits of inflammability of methane.
Mixtures to the right of the curves will not burn.

fire-extinguishing vapours. The removal of the oil is, of course, a mechanical problem, and cooling is generally carried out with water. The use of diluting vapours presents very great difficulties except in an enclosure, as, apart from diffusion, they are very easily blown away by the wind. The most important fire-extinguishing vapours usually used are carbon tetrachloride, carbon dioxide, steam, and methyl bromide; and a large number of proprietary designs of apparatus have been perfected for their use. Fig. C indicates the percentage of diluent necessary to prevent the combustion of methane, the first of the paraffin series. As the vapours of the paraffins, both singly and when mixed, behave in a very regular manner so far as their limits of inflammability are concerned, the order of effectiveness with methane gives a reliable indication of the effectiveness with any other mineral oil. Thus $12\frac{1}{2}$ per cent of carbon tetrachloride is equivalent to 24 per cent of carbon dioxide,

28 per cent of saturated steam, or 38 per cent of extra nitrogen. Slightly different figures would, of course, apply to particular oils. The methyl bromide cannot be so effective as any of the above since it can itself be ignited between very narrow limits under specially-controlled conditions, but it seems under working conditions to be a satisfactory extinguishing agent. Carbon tetrachloride and methyl bromide both belong to the same group of chemicals as chloroform and, like chloroform, they are more or less efficient anaesthetics and are also very toxic if absorbed in large quantities, or in small quantities over a long period. Obviously, care must be taken in handling them in confined spaces. Moreover, when carbon tetrachloride is applied to fire it may liberate phosgene, which is a dangerous gas. It is no doubt possible to obtain a canister respirator which will give protection against phosgene, but it is much better not to enter any confined space where it may be produced. Air diluted with large volumes of carbon dioxide will not support life, and a gas mask is no protection against this gas. The only protection is the use of oxygen apparatus.

For oil fires of very large magnitude only three extinguishing agents are commonly used, namely water, foam, and carbon dioxide. Carbon dioxide can only be used economically when there is some form of enclosure. Water and foam can be supplied through either hoses or fixed sprinkler heads. It is extremely difficult, however, to arrange sprinkler heads in such a way that they will deal effectively with a fire in an outdoor substation, because of the varying position at which the fire may break out and the effect of the wind. It is also very difficult to arrange any form of automatic installation in such circumstances. I propose to devote the rest of my remarks to the arrangements which should be made for outdoor substations, particularly where they are unattended.

The fires chiefly to be feared are those due to burst transformers and switch tanks. In one transformer fire 10 000 gallons of oil were consumed before the fire was extinguished; the following suggestions might have ensured that it would have been extinguished within a few minutes of the arrival of the fire brigade, instead of after 2–3 hours. For the top of the transformer and places where there is no "purchase" for burning oil, on the ground, or about the site generally, foam appears to be the best medium. Water is very valuable for cooling hot surfaces which may cause re-ignition, but should be used sparingly because it tends to disintegrate foam which may subsequently be used. Foam is most efficiently applied from the fire-engine pumps and generated either in an air-foam branch pipe or in a dry powder generator. Arrangements should be made with the local fire brigade, who should be instructed in the best methods of dealing with such a fire. Special branch pipes or foam generators, and a supply of foam chemicals, can be conveniently kept on site so long as they are regularly inspected and maintained in good order. The capital outlay is comparatively small. A good hard road should be provided from the main roadway to the site for the use of the fire engine, and the local fire brigade should be consulted in this connection. A reserve tank of water (rain water, if convenient) of, say, 10 000 gallons should be installed so that the fire brigade can commence to draw water from this immediately, while longer hoses are being run out to the nearest pond, river, or other large water supply. Such a tank is not very big, but will last a reasonable time when being used for foam production.

A proper extinguishing equipment having been provided, the next point to consider is how to handle the spilt oil after a tank has burst. This is, as the author states, best done by providing a layer of rubble or broken granite. If the fire is burning inside a transformer with a partly split tank there are two possible means of attack: (1) Carbon dioxide can be bubbled through the oil from the bottom of the tank to form a blanket; or (2) the oil may possibly be drained out into a sump. Both of these methods present some difficulties and neither has been completely tried out, but I believe they are worthy of further attention. Extra oil supplies should be cut off from a burning transformer, and in particular the valves between the transformer and oil cooler and/or conservator, where separate, should be closed. One important fire would have been much more quickly extinguished if the fire had not spread to the cooler, which, being structurally weak, collapsed and fed the flames on the ground. For this reason oil-cooling equipment should be separated from the transformers by a flameproof wall. (This applies also to the arrangements the author shows in Fig. 3.) Oil control pipes between the conservator, cooler, and transformer tank should be constructed with extended spindles so that they may be closed from a safe position in the event of fire.*

My belief that this procedure would be effective is based on actual experience of fires. In one case a transformer fire was only extinguished when a hose was attached to the transformer on the windward side and the oil was emptied on to waste ground adjoining the substation. A very serious benzol fire of an intensity far exceeding anything to be met with in a transformer oil fire was extinguished in 10–15 minutes by the Sheffield fire brigade using an adequate supply of foam from an air-foam branch pipe. This had been burning out of control for 2–3 hours before the supply of foam became available.

**Mr. H. Hoyle:** There is in the minds of some persons a doubt whether a fire of oil issuing from a container under pressure in the form of a spray can be extinguished by water only. In this connection I should like to refer to a test in which a 10 000-kVA oil-filled transformer was placed on open ground and a timber and bitumen fire allowed to burn beneath it for several hours, until the oil had attained its normal working temperature. Additional heating was provided just below the surface of the oil by immersion heaters of 50 kW rating which were switched on 2 hours before the test and left on throughout it. The transformer fire protection equipment comprised a dual system of pipework; on one pipeline automatic sprinkler heads were employed as fire detectors to indicate how quickly automatic apparatus could operate and control the water supply; on the second line of pipework special nozzles were fixed to command with water spray the whole of the exterior of the transformer case. When all was in readiness for the fire, water pressure was applied on the under-side of the oil in the

* Quick-acting throw-over valves might perhaps be used.

transformer tank from a supply at 38 lb. per sq. in. pressure; this caused oil to escape between the cover plate and the tank and form a fine spray which readily ignited from the fire below the transformer. The flames travelled back to the gasket joint and a "blow-torch" effect developed. About 15 sec. after ignition of the escaping oil all the detector sprinklers had operated, but it was decided to allow the fire to burn to its maximum intensity, which was reached after it had been in progress about 3 minutes. The valve controlling the water supply to the water-spray nozzles was then manually opened, and a few seconds later the fire was completely extinguished.

With regard to switchgear, when a switch fire does occur—and however remote may be the possibility of this occurrence the risk is always present—water scientifically applied in the form of a high-velocity spray to deal with the outbreak and extinguish it immediately is far more desirable than the use of other methods of doubtful efficacy.

**Mr. A. F. Carter:** I should like to make the suggestion that money would be well spent on research to discover a liquid for filling our cables, transformers, switches, etc., which will be a good insulator, and at the same time non-toxic and non-inflammable. Within reason price is not very important, especially if the substance turns out to have a good life.

[The author's reply to this discussion will be published in a later issue of the *Journal*.]

## NORTH-WESTERN CENTRE, AT MANCHESTER, 2ND MARCH, 1937

**Mr. W. Kidd** (Manchester): I agree with the author that we should not allow ourselves to be stampeded into spending enormous sums of money and making awkward arrangements of substations and power stations to guard against fire. It is not the possibilities of fire we are concerned with but the probabilities. In this area there are about 350 substations, and in a period of about 30 years there has only been one fire.

The author states that he has no knowledge of consequential damage caused by fire. He is, I hope, not unmindful of the fact that when an electrical fault does occur on a system it is by no means unusual for a second fault to occur in another part of the system; and whenever there is an electrical fault there is a possibility of fire.

Dealing with the prevention of fires, the first point to be considered is the equipment; if one does not install good equipment trouble is only to be expected. Here I should like to have a tilt at the switchgear manufacturers who, a decade or two ago, assigned ratings to circuit breakers for which they had not the slightest justification. As a result there are many thousands of existing installations equipped with the older type of plant where the risk of fire is greater than it need have been. The information I have collected in connection with fires suggests that they originate from troubles in insulation, bushings, current transformers, and cable boxes. On the older type of gear it was the fashion to use oil-immersed current transformers of the wound type, and, owing to the increased capacity of systems, it naturally follows that such items are now an exceptionally weak link. It would be advisable to eliminate this small type of current transformer as quickly as possible and, where practicable, substitute bar-primary type transformers. Voltage transformers were also used to a much greater extent than was necessary. I have knowledge of one installation where about 114 voltage transformers have been replaced by not more than 20, and still the same facilities are available. We have busbar protection in our 33-kV substations, and it has proved to be effective on one or two occasions. I do not, however, know of any such system that is sufficiently reliable and reasonable in cost to be used on generating-station busbars.

Turning to methods of limiting the extent of fires, one line of attack is to introduce a great deal of sectionalization, and this should extend right through the system. Large power stations ought to be designed on a unit system, each generator having its section of switchgear, both main and auxiliary. The sectionalization of a system can be carried out comparatively cheaply; in most major substations there are duplicate busbars with section switches, and it has been proved not to be impossible to divide the system without incurring big expense, by making full use of the various sections of busbars. It is sometimes overlooked that switchgear has an economical commercial limit of capacity for various voltages. For 400 volts I should put the limit at something like 25 000 kVA, for 6 600 volts at 250 000 kVA, and for 33 000 volts at 500 000 to 750 000 kVA. Beyond these capacities one has to pay abnormal prices for switchgear and this necessitates the division of low-voltage cable systems into sections, each fed by not more than 3 000-kVA transformer plant; at the higher voltages, the sections should be fed by plant of not more than, say, 20 000 kVA capacity. If that is done, and I think it can be in many cases, it will have a great effect in limiting the fault current and minimizing the risk of fire from electrical breakdowns.

Although a great amount of damage has been done by the spreading of fire via cables, there is little chance of fire starting in a cable passage if the cables are metal-covered. All inflammable covering at present existing in cable passages should be removed.

Regarding switchgear layout, the practice of installing vertical cable-boxes in connection with metalclad gear is rather a bad one, and some modification might be considered which would enable cables to be taken away from the switchgear as quickly as possible. In a recent installation I endeavoured to get the makers to arrange the boxes horizontal, so that the cable could be laid straight away through a vertical dividing wall into the cable passage. Unfortunately, the space and the time available prevented this, so we did the next best thing, which was not only to have a solid division between the various switch units but to carry the enclosure right round the back of the unit between the circuit breaker and the cable box; this arrangement shields the cables and will, I prophesy, become standard. In that same case, instead of putting the cable trenches below the floor, as is usual, we used the floor as the bottom of the cable trench and built a brick wall to form a cable passage behind the unit.

I think that cable passages ought to be divided, at least within the precincts of the substation or power station.

All switch rooms should be heated sufficiently to keep the gear dry. We use tubular heaters with thermostatic control, and, in large stations, time switches to cut off during peak-load periods. Which method of section-switch division does the author prefer?

If the interconnectors in Fig. 5 are cables then, I think, additional switches should be fitted to control both ends of the cable busbars. My practice with large transformers is usually to fit cable boxes on the transformers instead of using bare connections. Operators regard this practice as a disadvantage from the point of view of disconnection. Does the author also prefer the cable box?

My inquiries regarding Pyranol showed this to be very expensive. I hope that the oil industry will be able to put a non-inflammable oil on the market.

Has the author satisfied himself, by experiment or otherwise, that the rise of pressure during a fault in a switch house is slow enough to be relieved by the vents he suggests? My experience of damage to buildings has been limited to that resulting from faults in spouts, and in such cases there was proof that vents were useless.

With regard to fire-extinguishing, one ought to try to grasp the fundamental principles of this subject before deciding which system to adopt. Oil does not burn; it vaporizes, and the vapour burns. The amount of oxygen available must be reduced to prevent combustion, and the temperature must be lowered to prevent re-ignition. $CO_2$ has advantages for switchgear on account of its ability to get to all parts of the gear. This is not always practicable with high-pressure water systems, particularly on vertical metalclad gear. Moreover, the water system cannot be confined to a single affected unit; not less than three units will be drenched, and most of us would hesitate to return drenched high-voltage switchgear immediately to service. On the $CO_2$ system enough gas must be supplied to maintain over 17 per cent $CO_2$ dilution of the air for a sufficient period to prevent re-ignition. A fixed water installation is undoubtedly the most suitable way of dealing with turbine oil fires. It would be almost impossible to get at the source of the fire by any other means owing to the presence of heat, smoke, and plant. As oil fires are accompanied by dense black smoke a small fan should be installed in all switch rooms to remove fumes after a fire, and allow people to enter without delay. The switch must, of course, be outside the building, and the fan not used for normal ventilation.

**Mr. W. A. Coates:** There is one good arrangement which the author has not included in Fig. 1. In most primary substations, and main stations, the feeders are duplicated, and it is possible to rely, temporarily at any rate, on half the total number of feeders. It is therefore practicable to arrange what is usually termed a single-breaker double-busbar scheme in a room, separated down the centre, a row of breakers and one set of bars being on each side (see Fig. D). The connection through the barrier is made with some non-inflammable form of insulation, such as a condenser bushing. There is perfect subdivision, and it is quite easy to segregate half the switchgear, leaving the other half usable. In all cases where there are fireproof subdivisions, provision has to be made for tripping out all the gear in one section from another place. I doubt whether it is wise to rely, even for a few minutes, on a lead-covered cable. I would feel inclined to arrange a remote mechanical tripping device so that from one side the circuit breakers on the other side could be opened. This scheme would be entirely free from any risk arising from the cables being damaged.

I agree with the author that most trouble in switchgear is caused not by circuit-breaker failure but by insulator failure. In fact, most occurrences called explosions are not, strictly speaking, explosions at all, but are the effect of very rapid expansion of air around the arc. A big arc in free air can quite easily push a window outwards.

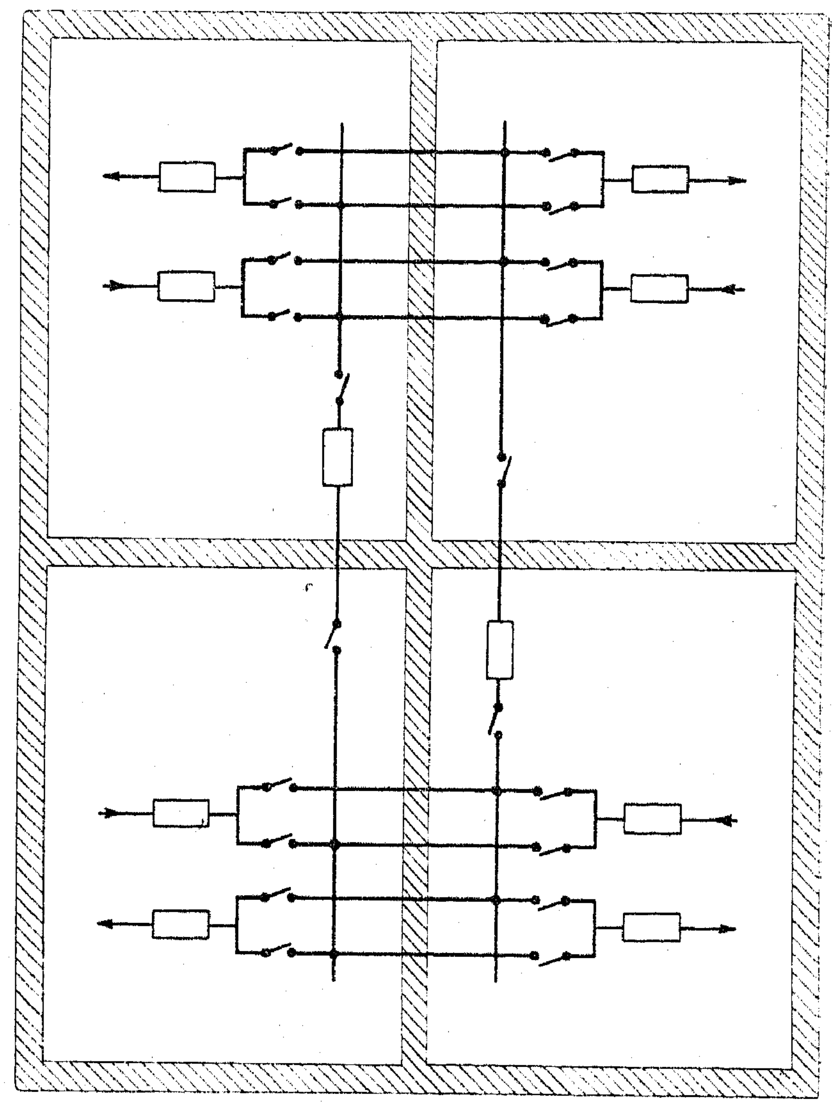

Fig. D

Where there are doors in fireproof divisions they must not be of the swinging type; they should be sliding doors arranged so that they can drop down into place on the burning-out of a fuse element. Swing doors must not be used because they are very liable to swing open under the influence of air expansion, allowing the fire to spread. The suggestion that the entrances to cable trenches, tunnels, and the like, should be blocked up with light plaster or very weak cement seems wrong because of this violent air movement due to an open arc. I feel that any blocking in such a place must be backed up fairly well mechanically. It is all right to close the final interstices with plaster, but there must be something more solid behind. Without careful maintenance the safety features of the most perfect switchgear are lost.

Oily waste, cigarette ends, etc., readily accumulate in the cable trenches.

Attention has been drawn to the fact that water is good for putting out an oil fire, if one can get at the oil itself. Saponine foam is objectionable because, though it puts out the fire, it makes a mess of everything in the vicinity. I would sooner take the risk of water on the insulation for a short time, than use saponine foam. Provided $CO_2$ is maintained carefully to ensure that it remains in the bottles and does not disappear gradually into the air, it is undoubtedly the best extinguisher, but it is also the most expensive.

In reply to Mr. Kidd's criticism of circuit-breaker designers who applied ratings for which they had no practical justification, I would point out that the power-station authorities refused to give us opportunities of testing our gear. Someone had to take a risk, and the people who did probably did the industry a good service, for very few "guess-rated" circuit breakers started trouble.

**Dr. S. F. Barclay:** The need for taking precautions to reduce the probability of fire in power stations and substations is obvious, but when all such precautions have been taken we are still left with a fire risk. Thus the main issue is whether or not fire-extinguishing equipment is justified having regard to its cost, in relation to the financial and other loss which fire could cause. The important point is not what is the degree of probability of fire but what is the probable extent of the disaster which could attend fire. To illustrate this point I will refer to the analogous case of the fire risk aboard ships. Statistics show that this risk is all but completely negligible—in the last 40 years there have been only 5 cases of serious fire in passenger-carrying vessels of the merchant navies of all countries. Instead, however, of the leading steamship companies saying that there is no need for them to extend their provisions against fire from the realm of precaution to the realm of extinguishing, we find them actively engaged in fitting the most up-to-date automatic fire-extinguishing equipment. The degree of probability of fire does not count: the question of material loss hardly enters into the matter: the bald issue is that the possibility of serious fire aboard a passenger-carrying vessel cannot be tolerated in the face of the relatively small cost of installing equipment which can surely prevent it. I submit we have the same state of affairs in our principal power stations and substations. The possibility of a disastrous fire cannot be tolerated having regard to the low cost of installing fire-extinguishing equipment.

The fire risk must be considered in relation to the abnormal as well as to the normal. Apart from the inherent risk, we have to take into account human frailty, human malice, and enemy action in time of war. So long as we have in our power stations a big volume of inflammable oil and inextricably interlinked with it we have the means of ignition in the form of superheated steam pipes and in the form of electricity, for so long shall we have the possibility of disastrous fire whatever precautions may be taken, unless the equipment also includes effective fire-extinguishing apparatus.

Some reference has been made to the form fire-extinguishing apparatus should take. There is a tendency amongst certain thinkers to regard a fire outbreak as something to be taken as part of the day's work—press a button, extinguish the fire, and return to normal conditions 2 or 3 minutes after. Such a state of mind is not in accord with realities. The probability is that any oil fire will cause such a deposit of soot and other carbonaceous matter on bakelite insulators, etc., that not only the gear immediately involved in the fire but that surrounding it will be unsuitable for use until it has first been thoroughly examined, cleaned, and tested. The more switchgear is improved and the more safeguards against fire are taken, the less becomes the probability of fire, but such methods cannot reduce the degree of disaster which could follow a fire outbreak, in the absence of effective fire-extinguishing equipment. When a choice is being made between different types of fire-extinguishing apparatus the one issue which should dominate all others is certainty of fire extinction when the fatal day comes. Too often engineers are influenced by the performance of apparatus under ideal demonstration conditions, and are apt to overlook the important fact that years may go by before the gear may be called upon to operate, while the attention given to it in the early days of its installation may later be relaxed.

**Mr. L. Romero:** In many cases there are almost insuperable difficulties in applying physical segregation to existing switchgear plant, and under these circumstances the best possible fire-fighting appliances (preferably automatic) should be installed in the major stations. Does the author know of any case of a serious fire occurring where an efficient automatic fire-fighting installation was installed? An efficient automatic $CO_2$ or similar installation should put out a fire before it has had time to do any damage to adjacent switchgear.

In order to safeguard the building structure from the effects of an explosion the author advises the installation of windows opposite switchgear to act as safety valves and so protect the building structure itself from damage. This seems to be very sound advice, but it conflicts with the instructions given by the Air Raid Precautions Department, who tell us we should brick up or sandbag the windows in switchgear houses. It would seem that what is wanted is a window which will act as a safety valve to internal pressure and at the same time be resistant to blast and splinters from bombs falling outside.

Can the author give us any information about the conditions which led to the three principal examples of building destruction which he mentions on page 297? Were these, in his opinion, explosions of gas collected inside tanks, cubicles, or other small confined spaces, or were they due to the accumulation of an explosive mixture in the substation itself? It would also be interesting to know whether the author has any theory as to what insulating materials formed explosive gas, e.g. bitumen compound or oil. This destructive-explosion danger from switchgear is rather a new thing to most of us, and it is desirable that as much information as possible regarding explosions that have actually occurred should be made available to the rest of the industry in order that the most effective steps may be taken both to guard against their occurrence and also to limit their destructive effect.

**Mr. S. Farrer:** The amount of provision necessary against damage to equipment by fire is largely an economic question of localization and duplication, involving sectional schemes to reduce the probability and extent of dislocation should damage occur. The question of sectionalizing the switchgear busbars suitably is receiving more attention than hitherto, but even now with many existing arrangements a fair degree of localization of fire risk is obtained for individual circuits. Small metalclad switchgear built on the unit principle automatically gives a fire-screening effect between circuits. In the same way even large metalclad units may conveniently be arranged with side frames which include steel sheets and so provide segregation between circuits.

It is gratifying to note that the paper recognizes the comparatively satisfactory performance and safety of existing types of switchgear and circuit breakers in this country. Consequently, although it refers in considerable detail to the causes and effects of fire damage to this type of equipment, there is no suggestion that any sweeping changes would be desirable to types at present in common use, namely metalclad switchgear and oil circuit-breakers. On the basis of experience I strongly support the author in this, but I agree that, depending on circumstances, more effective screening might usefully be carried out. Circuit breakers which include oilless arc-extinguishing must necessarily have their own special failings such as the difficulty of providing heavy normal current ratings without suitable interlocked switches or providing very high making and breaking capacity. Taking into account the facilities for short-circuit testing available in the past, the old oil breakers have performed reasonably satisfactorily.

I should like to amplify a statement in connection with busbar protection in which the author mentions that a busbar fault inevitably results in disconnection of all circuits. It should be noted that a protected zone with ordinary means of protection includes much more gear than the busbar proper. A fault occurring between an insulator which may be isolated from the busbar (e.g. a circuit-breaker insulator) and the location of the current transformers could be isolated either by opening the breaker or by isolating it; the busbar section may be reconnected as soon as this isolation has been carried out. In the ordinary way this possibility may not be known immediately, and an unnecessarily long shutdown may occur. This can be overcome by utilizing a "frame leakage" system for busbar chambers, lightly insulated from switchgear frames, together with one of the ordinary balanced systems. Operation of both systems would indicate a busbar fault proper, but operation of the latter only would indicate that after isolation of one or more circuits the busbar section could continue in service.

I am rather surprised that the author mentions Doble testing but does not refer to bridge methods, such as the Schering bridge, for making insulation tests. The compactness of the former lies largely in the fact that only a limited voltage value (I believe 10 kV) is used for the direct measurement of watts loss. In my opinion insulation tests of power factor or watts loss at any one voltage are not a satisfactory criterion of insulation condition, particularly if this voltage is only a small proportion of the working value. I have known cases where insulators with an unsatisfactorily low strength gave a low power-factor reading at any one voltage but the true condition was revealed when results were taken at several voltages, on account of the manner in which the power factor changed with voltage. On the other hand, perfectly good insulation may have high power factors which are more consistent at different voltages.

**Mr. O. Howarth:** The author does not seem very enthusiastic about busbar protection, judging by his references to it in the last paragraph on page 297. It is possible to equip a new installation with satisfactory busbar protection, but the difficulty arises when one attempts to apply busbar protection to existing equipment. Here one may even be increasing the risk by putting additional current transformers on the high-voltage system.

I think we sometimes overlook the obvious in providing for automatic isolation. We must remember that faults can be isolated by the staff if they have full indication of what is happening. Not very long ago there was a case of a fire following two faults. After the first fault had been cleared there was something peculiar about the load on the machine in that the ammeter on one phase was indicating more than the ammeters on the other two phases. Ultimately a second explosion occurred, and afterwards the earth resistance was found to be burnt out. There was a lapse of several minutes during which the staff were wondering what was happening. Had there been some earth alarm bell or similar indication to the staff that there was an earth on the high-voltage system, the extent of the disaster might have been very much less than it actually was. Rather than let the earth remain on the system the operating staff at any station would shut the system down, and thus give themselves a chance of restoring supply in a matter of hours instead of days as was the case in the particular instance I have mentioned.

With regard to the Doble test and the desirability of testing at different voltages, Doble testing does not mean carrying out a rigorous test to determine the characteristics of an insulator: it means ascertaining by periodical tests whether any change is taking place. If the power factor goes up, owing to the insulation resistance going down, then it is time to change the insulator. One of the defects in the schemes I have seen is that it is necessary to shut down a section of the system in order to make the test. It seems to me that, at any rate with the open type of gear and perhaps at a little more expense with metalclad gear, arrangements can be made for a routine test of the various insulators to be carried out without interference with the normal supply. Insulators are invariably mounted in a metal ring or housing, and if this is insulated from the general body of earthed metalwork the current coil on the wattmeter which is used can be connected in between that ring and earth; and a voltage transformer, which is connected between the phase on which the insulator is installed and earth, can be used to supply the voltage circuit of the wattmeter. The readings can be taken, preferably at the light-load period, without in any way interfering with the supply. In other words, they can be taken when the insulators are in normal service.

The arrangement of the voltage transformer is im-

portant. It would be of no use to use a 3-phase voltage transformer and pick out the artificial star point, because little differences which might occur in the voltage from any phase to the star point on the secondary, due to a change in the symmetry of the system voltages, would render the readings too inconsistent to be of any use. Provision should be made for a voltage transformer to be connected between the particular phase that is being tested and earth, assuming the system is run with the star point earthed. If it is earthed through a resistance, to get accuracy it will be necessary to ensure that no current is passing through the earthing resistance when readings are being taken.

**Mr. F. S. Edwards:** I regard the maintenance of the insulation in good condition as the first line of defence against fire, and my remarks will be confined to the last section of the paper where the author discusses briefly the routine testing of insulation.

While I admit that no form of testing has so far been devised which does not suffer from some objections, I cannot agree that the method mentioned in the paper, namely the use of the Doble tester, is the most promising. This apparatus consists essentially of a very sensitive wattmeter and microammeter, which indicate almost directly the losses and capacitance of the sample when it is subjected to a voltage of 10 kV at 50–60 cycles per sec. The necessary voltage is provided by a transformer incorporated in the equipment. From the two measurements of loss and capacitance the power factor is calculated very readily.

The Doble apparatus has been used to a considerable extent in the United States, but in this country another method has been tried, namely a portable form of Schering bridge, with self-contained transformer, air condenser, ratio arms, and galvanometer. Such a bridge operating at 5 kV was designed and constructed by Dr. Dannatt 9 years ago, and an article in the technical Press about 2 years ago* discussed the difficulties of site testing of bushings and described and illustrated this particular bridge.

The advantages of the Schering bridge are that satisfactory sensitivity is attained at 5 kV, and as a null method of measurement is inherent in the apparatus the exact calibration of the most delicate part of it is unnecessary. Furthermore, such a bridge can easily be made to read $\tan\delta$ directly [$\delta$ being $(90° - \phi)$ where $\cos\phi$ is the power factor], and in some cases can be made to read the load capacitance directly also. An accurate knowledge of the voltage is not needed, and the low voltage at which reliable readings can be taken makes it specially suitable for tests on 6 600- and 11 000-volt bushings for which the 10 000 volts of the Doble tester might be inconveniently high. The problems of the fitting of electrodes and interpretation of results are common to both methods, but in my opinion the bridge method is the more convenient and satisfactory of the two.

The biggest practical difficulty in both cases is that most switch bushings can only be tested with one pole permanently earthed, so that stray earth currents may completely vitiate the results unless suitable screening is arranged, but this particular problem appears to have been satisfactorily solved. It is desirable to provide insulated low-voltage electrodes so that this trouble will not arise, and such arrangements have in fact been made in certain metalclad switchgear.

In conclusion, I can confirm the author's remarks on the desirability of maintaining the temperature of switch houses above the dew point. It is my experience that when a substation is warm and dry the bushings are usually found to be in good condition, but when the air is cold and damp the bushings are frequently in an unsatisfactory state.

**Mr. T. W. Ross:** I will confine my remarks to the electrical protection of the busbar zone.

I agree with the author that the subject is a very complex one; nevertheless I consider that it is desirable to provide means for automatically tripping the circuit breakers carrying fault current and associated with a defective busbar or section of busbar. The fires which have occurred owing to defects on switchgear would have been prevented if some means had been provided for automatically disconnecting the supply to the fault. A time-delay in the clearing of a fault is not ideal, but protective gear having a delay of a few seconds is better than no protection at all. If, therefore, busbar-zone protection cannot be applied some form of back-up earth-fault protection should be provided, with current settings low enough to operate on minimum earth-fault current and a time-delay sufficiently long to avoid unwanted tripping.

The problem of busbar-zone protection is not entirely understood by many engineers. One of the points they often overlook is that a fault on the line side of the circuit breakers cannot be cleared by the busbar-zone gear unless it also trips the circuit breaker at the other end of the line. This is difficult to accomplish unless a pilot circuit is available, and in many cases the fault can only be cleared by back-up protection at the distant point. It should also be understood that when the busbar zone includes generator circuit-breakers it is essential to arrange that the busbar-zone protective gear also trips the generator field circuit breakers.

The author states that one reason why busbar-zone protection has not been more widely used is the fear in the minds of operating engineers that the remedy may be worse than the disease, owing to the possibility of unwanted operation on through faults. Many schemes have been developed for removing this possibility, one of which is the use of relays connected in tandem. I favour a method by which each circuit breaker is provided with a separate busbar-zone relay, and we have developed a scheme on these lines which has been very successful in service. The inadvertent operation of any one relay thus results in tripping only its associated circuit breaker.

A point which has exercised my mind is whether or not the busbar-zone relays should trip all the circuit breakers on the busbar or only those carrying fault current. The latter alternative might leave the defective busbar alive from some source which had an insulated neutral, and although the earth-fault current would then be reduced to a value represented by the electrostatic capacitance current it might still be large enough to cause a fire. I am therefore inclined to favour the scheme which will trip all the circuit breakers connected to a faulty busbar or section of busbar.

* *Electrician*, 1935, vol. 114, p. 483.

There are two generally-accepted methods of busbar-zone protection, namely (a) frame leakage, and (b) balanced current. We have recently developed a scheme which combines the two. In this way we provide against the possibility of unwanted operation due to the lack of balance between current transformers during through faults, and at the same time the scheme can be applied by separate relays for each circuit breaker. The scheme also provides for the tripping of all circuit breakers on any busbar zone whether they are carrying fault current or not, and also has a simple arrangement for the periodical checking of both balance and operating conditions.

**Dr. J. L. Miller:** The author, in dealing with routine measurement in the field of the watts loss and power factor of insulation, makes no reference to the Schering bridge. In my opinion the use of this is to be preferred to Doble testing, and in this connection I support the views of other speakers.

The measurement of the characteristics of bushings on site is certainly an important question. In this way slow deterioration can always be detected, so enabling the bushing to be replaced before breakdown ensues. It is our experience, however, that bushings which leave the factory with a " good " power factor and a straight-line " cos $\phi$-voltage " characteristic do not deteriorate. I have had experience of such bushings which have shown no change at all over a period of 8 years.

**Mr. H. Pearce:** I feel it is wrong to leave to the operators the responsibility of deciding when and whether a main station busbar shall be shut down. If this decision had been taken out of the hands of the operators in the case of certain recent unfortunate occurrences, the resultant fires would not have been so disastrous. A heavy power arc if maintained for any length of time is bound to set fire to whatever is near. If one can restrict the duration of the fault one will probably prevent any serious occurrence. One other important point—when one fault has occurred it produces difficult conditions in all parts and in some cases burns out the earth connections, showing clearly that in many cases both the cross-section and the joints of existing earth connections are inadequate for their duty.

**Mr. A. G. Ellis:** The author observes that with outdoor substations the individual units of apparatus are usually so far apart that there is little risk of fire spreading from one to the other. This is a good thing because in high-voltage substations, with bare incoming lines, the provision of barriers is a very difficult problem, especially in cases of cramped sites. I should like to ask the author whether he knows of any outdoor substations of importance that have been treated by putting in intermediate barriers.

There is a " semi-outdoor " class of design where the transformers, for example, are put into cubicles with open tops and open ends. This makes a very good design. The open end is enclosed by a low parapet wall to prevent oil spreading, and the cubicle itself is drained into a sump. It is very desirable to have a proper oil-drainage system.

There has been some mention in the discussion of fire spreading through the cable ducts in consequence of burning oil running down them, and I should like to mention one way in which we have dealt with this point In the case of cables coming in from the floor and rising vertically to the transformers a parapet has been built round the cables in the form of a large drain pipe, to a height of 5–6 ft. This would be quite effective in preventing the oil spreading down the cable ducts in the event of a burst tank.

I do not quite like the statement (page 295): " Transformers are peculiarly susceptible to faults between turns. . . ." I do not think the author really means this literally. I would rather he had said that " Of the relatively few faults that occur in transformers the majority are faults between turns." It is a matter of experience that the modern transformer is very immune from trouble.

Regarding the question of automatic fire-fighting equipment, I should like to mention an attachment which has been fitted to some large transformers. Contacts are attached to the explosion diaphragm for automatically operating the fire-extinguisher in case of fire when the explosion diaphragm bursts. The author omits to mention explosion diaphragms on transformers, and I can only infer that he sets no great value on them. Although they do not afford full protection against the bursting of the transformer tank they do give partial protection against the tank bursting badly. In my experience there have been very few cases of burst tanks; that is to say, bursts where the oil has got loose and done a lot of damage. There is a time-delay between the occurrence of the explosion and the bursting of the explosion diaphragm, and the sides of the tank may be bulged and the stiffening ribs partially ripped off. Cases of serious bursts of transformer tanks due to explosion are rare.

With regard to non-inflammable oil, which the author refers to on page 295 under the name of Pyranol, one of the difficulties is that it acts as a solvent on certain varnished insulation. This may be a drawback in connection with small transformers whose windings have to be treated with varnish; but many of the medium and large transformers are built without varnish-treated coils, and from this point of view could be filled with Pyranol. The problem at present is, as the author points out, that Pyranol costs many times as much as mineral oil, so that to fill a medium-sized transformer with non-inflammable oil would increase its cost very considerably, in some cases up to nearly double. The question is whether the extra cost is commensurate with the degree of risk involved.

The author refers to air-cooled transformers (without oil); natural air-cooled transformers in the smaller sizes are frequently used in London for basement substations, for large blocks of buildings, such as flats and stores. On some parts of the Underground Railways for many years the practice has been to install air-blast (fan) cooled transformers (without oil), the idea being that by so doing the fire risk is diminished. Dry air-blast transformers have also been used recently for boiler-house auxiliary supply. This type of transformer is not inherently safer unless it is properly maintained and the windings kept clean. Cases have occurred where the windings have been allowed to become clogged up with dirt and dust, the air blast has ceased, and overheating

has developed, with ultimate failure of the insulation and windings. The risk with the dry air-blast type is, unless it is properly maintained, possibly no less than with an oil-immersed transformer.

**Mr. D. R. Davies:** Although the paper purports to deal with all classes of electrical plant, it is obvious that the author regards switchgear as the " bad egg." Unfortunately, we have to admit that disastrous fires have occurred in cubicle gear and metalclad gear, both indoor and outdoor, and although in the past the oil circuit-breaker has been regarded with the most suspicion the majority of fires on cubicle gear have been due to open arcing, and in metalclad gear have been due to failure of insulation. About 90 per cent of the failures in metalclad gear have occurred in spout insulators. The oil circuit-breaker risk is practically eliminated with the modern tested breaker, especially if this is fitted with an efficient arc-control device.

I agree with the author's statement on page 290 regarding the necessity of subdivision of switchgear, but I do not agree that subdivision in the case of metalclad gear is restricted to the segregation of groups of switchgear only.

Fig. E shows metalclad gear using single-break oil circuit-breakers; it will be noted that the busbars and their selectors are separated from each other and from the breaker, and that the cables and voltage transformers are separated. This design also permits, within reasonable dimensions, phase separation throughout, a feature I consider essential for all switchgear which demands a rating of 750 000 kVA and upwards. I would also prefer to eliminate all air insulation for voltages of 33 kV and upwards. Moreover, in important substations and all power stations, single-core cables only should be brought into the switch house.

Of the illustrations in Fig. 1, that shown at (*d*) seems to be the minimum we can do to guard against a lengthy shutdown.

It is interesting to have the author's statement that in his experience no serious fire has started in the cable chamber, and I should like to ask him why he condemns the use of aluminium alloys having a melting point of 650° C. in metalclad switchgear, and is yet prepared to use lead-covered cables, the lead, of course, having a melting point of just over 300° C. It must be appreciated that where currents exceed about 1 000 amps. the choice of materials for casings is rather restricted, and if we cannot use an aluminium alloy the only alternative appears to be gunmetal; but here again, although this has a melting point of 900° C., should we gain much by changing from 600 to 900° C.?

It is a pity the author has included Fig. 4 in his paper, because whilst this design was probably the best available at the time of its installation we cannot regard such a layout as typical of modern practice. The arrangement is very extravagant in regard to space, since it requires a volume of approximately 140 000 cu. ft. Metalclad gear using a single-break breaker would require a building having a volume of only 44 000 cu. ft. The design shown in Fig. 4 also has the disadvantage in that the connection from the top busbar chamber passes through the bottom busbar chamber.

A $CO_2$ installation appears the most suitable form to deal with switchgear fires, since it is less likely to damage insulation on adjacent equipments. I have a preference for a non-automatic installation arranged with the $CO_2$ release in the control room. Also for important stations there should be duplicate batteries of cylinders, each battery having sufficient capacity to fill one section. If this fails to extinguish the fire, the second battery can be brought into service.

I think Fig. 5 would have been more representative of British practice if the author had shown diagrammatically a star reactance scheme, as this is undoubtedly the standard layout in this country. Such a scheme also lends itself very readily to the subdivision of sections into independent switch-houses.

**Mr. C. H. Flurscheim:** I should like to comment on the numerical probability of an oil circuit-breaker causing a fire when opening on short-circuit. We have found that if a breaker is fitted with cross-jet explosion pots the fire risk is almost negligible. Proof of this is afforded by an analysis of the short-circuit tests made on such circuit breakers under the conditions of severity prevailing on a large test plant. The tests were made on both standard and experimental designs, and included all development tests on the interruption of powers from almost zero to over 1 000 000 kVA. Only one fire occurred in the last 1 000 tests: this happened on an experimental design which stuck partly open, the back-up protection being delayed $2\frac{1}{2}$ sec. This good safety record was achieved in spite of the fact that the tests were by no means trouble-free. Both mechanical and electrical defects occurred, including complete failure to interrupt in several instances. The record for plain-break design is not as good, showing 8 fires in 400 tests made over the same period.

This difference in fire risk is due to the different interrupting characteristics of the two types. If a cross-jet design fails to clear the tank pressure rises slowly, allowing time for structural deformation and for the gradual escape of the gases. Fire will not occur if back-up protection operates within a reasonable period. If a plain-break design operates incorrectly, however, the pressure is liable to increase with explosive violence, and tank fracture may occur within a few cycles. While both types can be made almost fireproof by proper testing, this is particularly essential in the plain-break case.

Regarding conventional outdoor designs, the low fire risk associated with this class of switchgear is confirmed by our test experience.

**Mr. P. G. Ashley:** I should like to refer to the use of the portable Schering bridge for measuring the quality of varnish-paper bushings in position on site.

During the last 4 years tests of this nature have been carried out on about 2 500 bushings on 13 switchboards, the service voltage ranging from 6·6 kV to 66 kV. In some of the stations we have found bushings with values of tan $\delta$ so high as to lead to recommendations for their replacement, but on a number of switchboards the bushings tested were found to be in good condition. In one particular station where tests were made on a 33-kV board initially, and again after a lapse of 3 years, it was interesting to notice that the second set of readings was very little different from the first. A few bushings had

higher values, but the majority were slightly lower, probably owing to the fact that the load on the station had increased considerably in the intervening period, resulting in a generally higher ambient temperature. In another station individual tests were taken on the plug tests were made on these parts when they were received back in the works. First the portable bridge was used under laboratory conditions to check the values obtained on site. Bearing in mind that 3 months elapsed between the two series of tests, and that it was not possible to

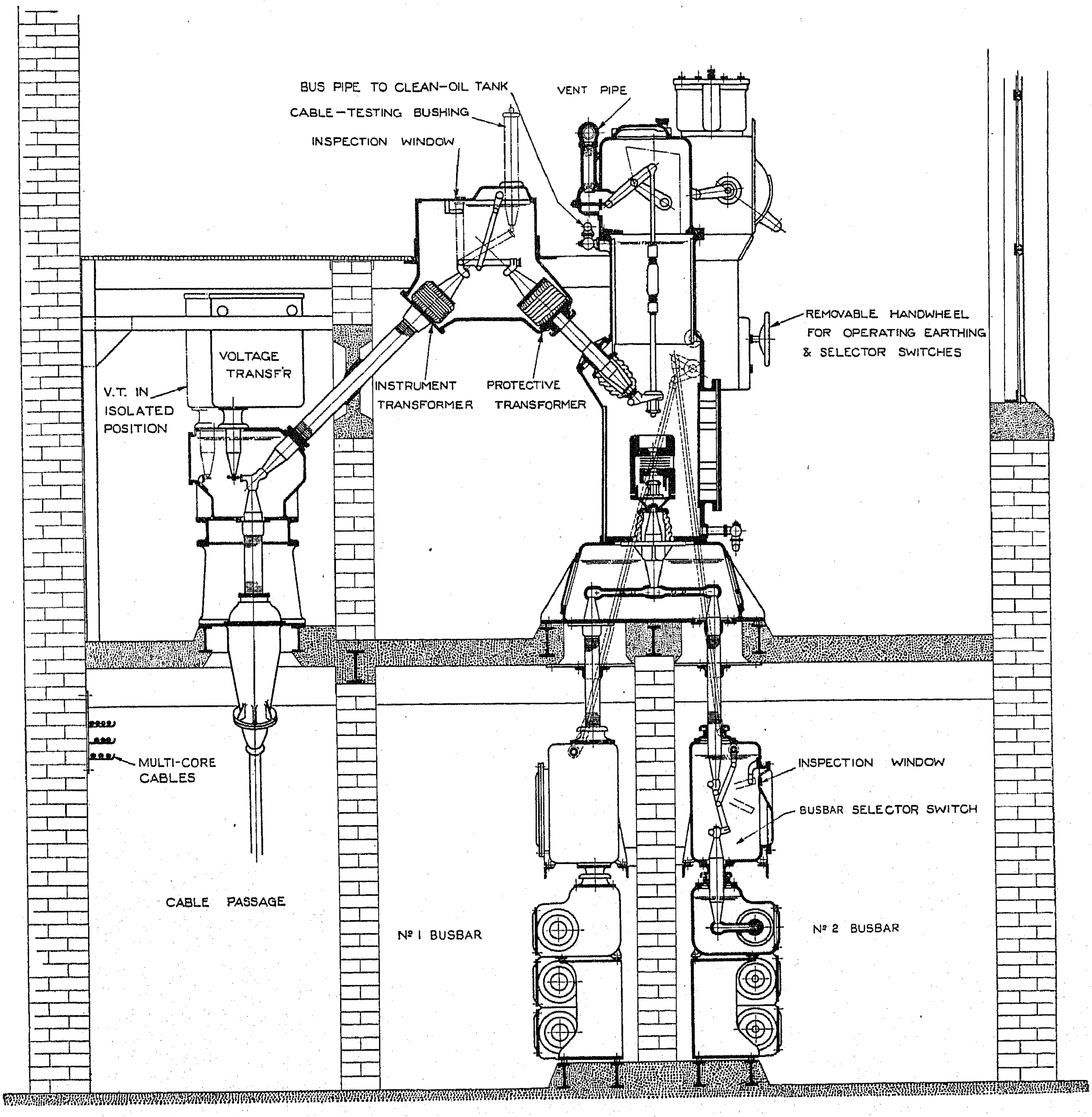


Fig. E

and spout bushings of a 6·6-kV board of very early construction. Out of 78 bushings tested, 84 per cent had values of tan $\delta$ from 0·05 to 0·25, 5 per cent had values from 0·25 to 0·50, and 11 per cent had values from 0·50 to 1·1. Some of these values are very high, and immediate steps were taken to replace three busbar chambers and a current-transformer chamber. Further fit the temporary electrodes in exactly the same position as on site, the results were very consistent, being generally about 15 per cent higher. In endurance tests on the individual bushings those with values of tan $\delta$ up to 0·50 safely withstood 11 kV for an hour, followed by 16 kV for an hour, and finally 22 kV for a further hour, although the value of tan $\delta$ increased by 25 to 30 per

cent. A bushing with $\tan\delta = 1 \cdot 1$ failed after 62 minutes at $6 \cdot 6$ kV, and one with $\tan\delta = 0 \cdot 85$ failed after 47 minutes at 11 kV.

These figures go to show that the portable Schering bridge will effectively discriminate between individual bushings in service; that the results obtained agree reasonably well with figures obtained under similar conditions in the laboratory; and that from the figures taken on site it is possible to judge with reasonable accuracy which bushings are in a condition likely to give trouble in service. Tests have not been confined to any particular class of bushing. We have found it no more difficult to test metalclad than outdoor or cubicle-type bushings. It is not always possible to test in exactly the same way as would be done in the laboratory, but a knowledge of the construction of the particular bushing and the manner in which temporary electrodes, if necessary, are fitted, enables the results to be properly assessed.

Some engineers consider it a major drawback that apparatus must be made dead in order to carry out dielectric-loss tests. I should like to emphasize, however, the necessity of periodic inspection and cleaning of any insulation, particularly where it is air-exposed, and I submit that the occasion of such cleaning is a convenient time for carrying out tests. It is not, of course, necessary to test all the insulators in a switchboard at once, and it surely presents no difficulty to clear various sections of the gear in sequence.

It has been suggested that the testing apparatus should be arranged so that periodic tests can be taken on any insulator while the gear is still alive. From each bushing a shielded lead would have to be taken back to the test apparatus, and on a moderate-size metalclad board of, say, 10 duplicate busbar units, with 90 spout bushings on the fixed portion alone, this would necessitate 90 leads with 90 change-over switches to permit of the leads being connected either to earth (for normal operation) or to the test set. The complication of such an arrangement would, in my opinion, be prohibitive.

**Mr. A. Upton** (*communicated*): An important point in connection with precautions to be taken against the danger of fire in switch houses is the circuit-breaker tank joint. It is an accepted fact that oil circuit-breakers are of robust construction, and their abilities to clear safely currents up to and well above their guaranteed rupturing capacity can be proved at any of the test stations now existing in this country; but it must be remembered that the joint between the tank and the top plate is, at the time of testing, in a healthy state, and the actual tightening of the studs is part of the test routine.

When switchgear is installed and in commission the responsibility for its operation and maintenance rests with the supply undertaking and it is up to them to see that the tank studs are kept absolutely tight; as in the event of the breaker clearing a fault the pressure set up is, in many breakers, sufficient to spray oil for a considerable distance, if this joint is not well made. This effect would appear to be greater on breakers employing flat face-to-face joints, such as the conventional square-tank type, than in the circular-tank design where a form of tongued and grooved joint is used. In the former design it is true that the large flat surface would tend to cool the oil as it passed across the joint, but the circular tank with its tongue projecting into the top plate groove (and the tank securing studs not tight) would act as a deflector and reduce the rate at which the oil would normally pass through a similar unrestricted gap, and in so doing reduce the amount of oil discharge. On the basis of this argument it seems desirable for the oil circuit-breaker to be screened on every side.

[The author's reply to this discussion will be published in a later issue of the *Journal*.]

## SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 8TH MARCH, 1937

**Mr. C. J. O. Garrard:** The author's argument is that electrical duplication of apparatus is essential in order to provide for maintenance, inspection, etc., and also for the failure of individual apparatus; but that to provide against the risk of fire it is sufficient to have two duplicate busbars, with their circuit breakers, situated in separate fireproof enclosures. He does not agree that the segregation of individual circuit-breakers in fireproof enclosures is necessary, and is prepared, it seems, in the event of a major disaster to lose the whole of one of the two duplicate sections. When one considers that the replacement of a section thus destroyed would take at least 6 to 12 months, during which time the station would be without duplicate facilities, one feels that greater subdivision of the fireproof enclosures might be financially justified.

It is remarkable that the author does not mention in his paper the stonework cellular type of gear. This gear, as it consists of a large number of fireproof compartments, has naturally a high resistance to fire, and contains less combustible material than a metalclad board. A further advantage is that all parts are accessible for cleaning and inspection. Certain serious switchboard fires have been caused by the deterioration of comparatively small insulating parts, which might have been avoided had regular examination of the parts been possible. Regard for the safety of operators also speaks for the enclosure of oil circuit-breakers. However well designed breakers may be, experience in short-circuit testing laboratories shows that it may be very unpleasant to be near one which operates at its full capacity.

The author very rightly observes that mediocre apparatus well laid out may be better than first-class apparatus badly installed. Whatever advances are made in the design of circuit breakers, it will always be wise to treat them with respect. Continental experience in these matters is of interest. The catastrophic results of oil fires in the open switch-houses in use, say, 20 years ago, led to the segregation of all apparatus containing oil; as, for instance, by sinking the circuit breakers in the floor. With the introduction of oil-less and oil-poor circuit breakers, stations are again being built with all the apparatus in one room. It is clear that financial considerations have largely determined this development. I feel, however, that a mistake may

have been made and that it would have been better to retain the segregation of the circuit breakers, as many types of failure are just as likely with oil-less breakers as with oil circuit-breakers, and necessitate the same precautions.

Fig. 1(*f*) might be improved by providing a separate fireproof chamber for each busbar-sectionalizing breaker. In this way the double busbars in either of the main switch rooms could be kept going independently of those in the other.

In large power stations the switchgear appertaining to each alternator and its corresponding feeders should be in a separate house. Interconnection of sections should be by means of reactors and reasonably long cables, in order not to have the reactors in the immediate electrical neighbourhood of the circuit breakers.

Insufficient attention has been given in the past to busbar protection. As an ordinary busbar has so many branches, the use of current-balance protection presents many difficulties. A possible solution may be the adoption of the "mesh" type of busbar, as used on some sections of the grid. The busbar (Fig. F) has as

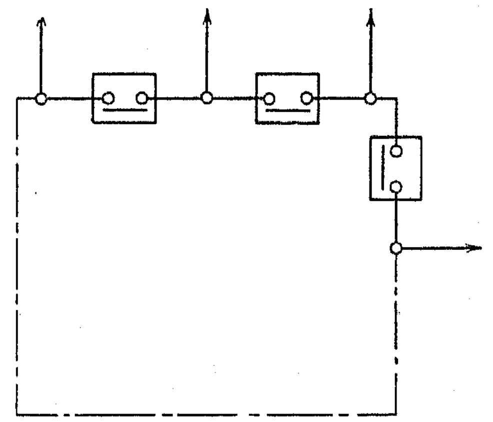

**Fig. F**

many sections as there are feeders, each section being treated from the point of view of protection as part of the corresponding feeder, and each feeder having two breakers. A fault on any section only affects one feeder.

On page 297 the author says that "one serious difficulty lies in guaranteeing that the remote end of connected feeders shall be cleared when a busbar fault occurs," and that he has an uneasy feeling that in adopting busbar protection he may be "putting all his eggs into one basket." A further explanation of these remarks would be interesting.

**Mr. D. Kingsbury:** In regard to the suggestions which are sometimes made that cellular gear is less inflammable than metalclad gear, it is worth bearing in mind that one of the fundamental necessities of cellular-type switchgear is that each section should be shut down and cleaned at regular intervals, and that the majority of unfortunate occurrences on switchgear have been due to misunderstandings associated with the shutting-down for cleaning and transferring of load from one section to another.

It would appear that, to be of value, busbar protection should be instantaneous in operation. Almost all systems of busbar protection, except possibly the Howard system, in which one lightly insulates all the metal portions and then puts a current transformer in the lead which earths them, rely on current balance and in the ordinary way the least trouble with auxiliary switching or small wiring connections will give the same degree of unbalance as a primary fault current, with the resultant clearing of all circuits connected to a section of the busbar. Systems have been devised in which one of the fundamental characteristics is that there are at least two lines of defence before a trip can occur. This seems to me to be most important. In the early days of the use of feeder protective gear of the balanced type there were many spurious operations. We cannot afford such spurious operations with busbar protection, because the resulting shutdowns would be so much more serious.

Following a recent fire in a switch-house there has been renewed support, on the part of certain engineers, for oil-less circuit-breakers. Investigation and tests in this country seem to indicate that existing designs have inherent disadvantages which more than compensate for their lack of oil-fire risk, and it is perhaps true to state that in this country, where continuity of supply ranks so high, manufacturers are not prepared to dispense with oil circuit-breakers. It is common for engineers to point to Continental practice as a means of indicating to British manufacturers their lack of enterprise in this direction, but had Continental oil circuit-breaker design at any time approached the excellence to be found in this country there would not have been the same need for Continental engineers to explore other means of circuit-breaking.

Another point worthy of consideration is the relative merits of round-tank and rectangular-tank breakers. When a round-tank breaker fails, the damage done to the building is extensive; it seems that since the breaker structure cannot distort to relieve the internal pressure it must eventually burst. The rectangular-breaker tank, on the other hand, can be built quite strong enough in all substation sizes to do all that is required of it in service. If it fails due to ill-treatment it does so comparatively quietly, and it can be arranged that the joint which opens owing to distortion is not that which is nearest the operator.

A small point to which I should like to draw attention is the damage which a fire does to the crane rail in a large switch-house. More than once the results of a serious fire have been made much more serious because it has been impossible to use the crane afterwards, and some arrangement to protect the crane rails, possibly by lengthening the span of the crane and setting the rails back into the walls, might be a distinct advantage.

There is another all-important point which should receive consideration from designers of electrical apparatus, namely the thermal capacity of the walls of containers in which there is electrical apparatus connected to systems having considerable potential fault kVA. Should internal arcing be set up it is imperative that a container shall be robust enough to withstand this arcing long enough to allow a circuit breaker to trip and clear the fault. Failure to do this must inevitably lead to a fire, and from this point of view transformers may be considerably more dangerous than switchgear.

The author suggests that a building should have plenty of windows in it in order to be safe from fire. I am inclined to suggest that, at least where $CO_2$ is used

for fire fighting, it might be better to dispense with windows and to build a comparatively light roof, or a roof with large flaps or lightly-held panels in it, so that the pressure could be relieved without making it more difficult to keep the fire-quenching medium up to its work.

In closing, I would refer to the possibility of fires in cable trenches in buildings. It must not be forgotten that although the neutral earthing resistance sets a limit to the current which will flow on the occurrence of an earth fault, a simultaneous earth fault on another phase (which is by no means unknown) will raise this limit to that of a full phase fault, and it is possible for the resulting earth current to strip cable leads and to start fires in this way. I suggest that careful consideration should be given to this point when cables are being installed and that, in general, the leads should be bonded to earth at one end only and insulated at all other points. With regard to the protection of cables in trenches from the effects of burning oil, experiments have shown that comparatively large pebbles, as distinct from granite chippings, will protect cables within 3 in. of the surface of the filling.

**Mr. W. Burton:** Mr. Garrard evidently wants even more subdivision than is provided by the author in the arrangements of switchgear shown in Fig. 1. Technically, Mr. Garrard is quite right, but the author takes a standpoint based on experience and observation and is careful to point out that expense sets a limit beyond which the designer cannot go. A large number of subdividing walls will provide a very safe station, but these walls have to be paid for and the expense is ultimately reflected in the price per unit. Fig. 1(*d*) with a little modification would, I think, satisfy Mr. Garrard and also the author. It is shown as a single-busbar arrangement, but it would be possible to add a second busbar; with armourclad gear the second busbar would be taken outside the middle chamber. It would of course have to be taken up, or down, or round, because obviously if there was a fire in that middle chamber with the second busbar passing through the position would be little better than with the simpler arrangement.

The author favours catch-pits filled with rubble or pebbles; I should like to ask him whether he considers that these are of any value for large quantities of oil. A small quantity of oil will certainly trickle down through pebbles and will probably be quenched, but when quantities of 2 000 to 10 000 gallons are involved is the oil going to trickle down quickly enough? The amount of stone in a catch-pit is something like 50–60 per cent of the volume of the catch-pit, so that a very large catch-pit is needed to deal with a big quantity of oil. It would be much better to leave the catch-pit open, make it deep enough, provide $CO_2$ or an emulsifier, and so assure efficient fire-fighting to deal with oil burning on the top. Suppose the oil does run through the stones, is it not a fact that the heat of the stones will in time vaporize the oil? The stones will become hot, cause explosions, and be thrown about.

Turning to the subject of busbar protection, there seems to be no satisfactory means available at present, but the Howard system is the most promising from a practical point of view. I should like to ask the author whether there is any fundamental reason why that system should not work.

**Mr. P. F. Harris:** I do not agree with the author that Fig. 1(*f*) represents "True sectioning in double-busbar application." It assumes that where there are two sets of busbars in one chamber a fire can originate in one set of busbars or in a circuit breaker connected to one set of busbars without affecting the second set. Once a fire starts, any of the apparatus in the fire section in question is liable to be damaged and put out of action. The arrangement shown in Fig. 1(*g*), with the busbars in separate fireproof chambers, is far preferable. If there are duplicate feeders it would appear preferable to avoid this amount of elaboration and adopt a single-busbar layout with proper sectioning and coupling, thus securing a much simpler arrangement with greatly reduced fire risk.

The possibility of misunderstanding with regard to the operation of cellular gear, and consequent accidents, is sometimes given as a reason against using this type of gear, in spite of its advantages from the point of view of being fireproof. If good interlocking is used and the maintenance staff is reasonably efficient, then either cellular or metalclad gear should give good service, there being no cause on this account to discriminate in favour of either. Experience of a number of installations has shown that, if there is room available, the claims of cellular gear as to fireproofness and general reliability in service rank very high.

**Mr. P. V. Barnes:** Dealing firstly with circuit-breaker fires, it is essential that the circuit breakers installed should be as similar and interchangeable as possible and that a good stock of spare parts should be kept, to ensure that a station or section shall be out of commission for a minimum period following a fire.

Regarding spacing, one of the best arrangements is well-spaced breakers without partitions but with each breaker or group fitted with individual $CO_2$ piping, preferably operated from the control room or, in the remote-controlled stations, thermally from the breakers themselves.

Has the author ever considered the immediate draining of oil from the damaged apparatus, making use of the excessive pressure caused by the fire or of a thermal release, and letting the oil run into the central draining channel of the building? The exclusion of air in transformer fires might be considered, to discourage any fire from maintaining itself. This could be done by putting every transformer of the oil-immersed type in a separate half-sunk cell with close walls, the difficulty of maintaining normal cooling being overcome by hinging the top cover and dropping this when the transformer was on fire. Even if the transformer burst, the cell would confine the oil to its gravel base and enable $CO_2$ or foam to be used.

One alternative method, for breakers, is not to sectionalize in the first place but to use sliding metal doors of the ordinary travelling single-rail roof type. These can be moved into position so as to isolate the fire section and not affect the rest of the station equipment, assuming that after the first explosion the men will be able to get within 15 ft. of the equipment,

sheltered by the movable sectioning. This method reduces first costs. Also, if $CO_2$ manually-operated gear is used, as soon as the door is in position the gas can work more effectively in the restricted space.

**Mr. J. Morton:** I should like to refer first to the arrangement shown in Fig. 1(*f*), as this is similar to a large scheme which at one time gave me a good deal of concern. I realized that in the event of a serious fire in either section of the switch-house a means of splitting the busbars into sections was advisable, but the slight risk of such a fire did not justify the necessary capital expenditure where heavy-current-capacity section switches of high kVA rating were involved which might cost £5 000–£6 000 per equipment. I found that a suitable arrangement of oil-immersed bolted busbar links with access from either side of a transverse wall would meet the case and be obtainable at 1/40th of the cost of a circuit breaker. Such an arrangement of links would necessitate a temporary interruption of supply should a fire occur, but we must not forget that the interruption of a water supply due to the bursting of a main supply pipe and its consequent damage to property is readily accepted by the average individual as an Act of Providence, against which claims cannot be made. It is therefore reasonable to suggest that a temporary interruption of electricity supply resulting from a serious fire should be credited to the same source. Such a voluntary shutdown would enable the necessary rearrangements for switching to be carried out calmly and safely, and a reliable supply to be restored in the shortest possible time.

As regards the question of cable trenches filled with sand or pebbles, where this method is adopted the safe loading of the cables is materially reduced owing to the heat insulating properties of the dry sand (this disadvantage is not quite so serious in the case of pebble filling). Further, the inherent movement of the cable resulting from loading would in time cause damage due to the puncturing of the lead in plain lead-covered single-core cables which have relatively large cross-sections and which are necessary for power-station use; this factor puts steel-wire protective armouring out of the question.

Finally, I would point out that the draining of burning oil from switches and transformers can only be done by suitable trenches filled with such material as will permit of the free flow of oil through it against a minimum friction head (this determines the minimum size of pebble which can safely be used). Burning oil entering such a trench is immediately extinguished, and the oil is partially cooled before reaching any outlet pipes provided between the trench and the ultimate drain pipe. This must be of such cross-section as will avoid decrease in the velocity of flow through the pebbles.

**Mr. E. J. Mathieson:** There are two short questions I should like to ask. Firstly, from the paper it would appear that the fire hazard in a major station is negligible; is it correct to assume that the major precautions are taken in the substations, so that in the event of an outbreak of fire in a substation this is automatically cut out of service and the fault thus prevented from endangering the major station?

Secondly, does the author know of any modern power station in Great Britain where at least the main line circuit feeders are screened from the meter panels? I have in mind one power station, laid down in 1932, where this is not so—there is no division between the meter panels and the circuit feeders.

**Mr. H. C. Fox:** Quite a good case can be made out in favour of the fireproof properties of the cellular type of gear, but its safety is largely negatived in the majority of cases by the specification that all main conductors shall be covered with insulating material of an inflammable nature, or such material shall be used as barriers between the conductors. The somewhat absurd situation arises that in most of these cases it is specified that all the auxiliary wiring shall be of fireproof material. I have met cases where the auxiliary wiring could not be passed as satisfactory until proof was given that a piece of the wiring could be held in a welding torch without taking fire.

**Mr. F. H. Mann:** With regard to the question of construction of buildings, hitherto little thought has been given to the possible disruptive effects of an explosion, and the consequences have been largely unpredictable. While in general the windows and weaker parts are the most susceptible to damage, this is not always the case. There is one instance on record where, owing to the failure of an oil switch, the walls of the station bulged just sufficiently to catch the roof on its return after a short upward flight. In that case, extraordinary to relate, the windows remained intact. Unfortunately for Mr. Kingsbury's hypothesis, the faulty switch in this instance had a rectangular tank.

Turning to the subject of fire extinction, of the various methods available the application of $CO_2$ seems to warrant very careful consideration, since its effect may easily be vitiated by unsuitable situation or by faulty layout. If, for instance, the gas is projected at the wrong angle, or at too high a level, it may easily be dispersed by the upward convection currents from the burning oil. I have seen jets installed at a height of from 5 ft. to 10 ft. and arranged to discharge at an angle of 45°, and it seemed possible that the gas from these jets might be shot upwards before it could be fully effective. If the jets are placed at a lower level and are arranged to spray on to the seat of the fire, the $CO_2$ would appear to have a better chance of evading convection currents.

So far as the effective use of sumps is concerned, Mr. Burton's point is a very real one. Is it not better to combine the pit filled with round pebbles or ballast with drainage, so that the oil is extinguished as it trickles through the pebbles and the possibility of saturation is removed? There seem to be two systems available, namely sumps large enough to contain the whole of the oil, which means extensive excavation, or the use of a drain to carry the oil away, in which case there may be danger of the oil vapour burning at the grids. In my opinion a combination of the two offers the best solution, but it would be interesting to know whether the author agrees with this view.

In conclusion, there is a passage on page 289 which is rather puzzling. This is where the author says "Technical perfection is neither possible nor economically practicable." Now if technical perfection is not

possible, how can he know whether it is economically practicable?

**Mr. W. Brown** (Birmingham): The author advocates the use of gravel or sand for filling cable trenches. Where this policy is adopted great care should be exercised, particularly where a considerable number of cables lie in one trench, otherwise very serious overheating of the cables may occur.

With regard to the relative merits of metalclad and cubicle switchgear, a serious fault on metalclad gear invariably calls for the attention of the manufacturers, but in the case of cubicle gear it is nearly always possible to effect a jury repair with the facilities at the hands of the supply authority. One of the disadvantages of cubicle gear is the extra space required, and consequent extra cost of fire-fighting equipment. On the other hand, with cubicle gear it is quite a simple matter to get at any connection or current transformer, whereas with metalclad gear this invariably entails a great deal of work in the running-out of oil or melting-out of compound.

Some form of busbar protection is clearly desirable, but I am doubtful as to the desirability of the systems that are at present available. There is a move towards making the provision of busbar protection compulsory under the Home Office Regulations, but it would appear to me that if every portion of the system is protected against excess of current so as to avoid danger (see Regulation 8) the Regulations are complied with.

One point which requires attention is that in which generators are fitted with discriminating protection only, which will not operate in the event of a through fault; the Regulations are not complied with in this case unless some form of back-up overload protection is fitted. This case can be covered by the use of unrestricted earth-leakage relays, but the use of such relays has the disadvantage that one has to use an appreciable time-delay in order to back up on the feeder protection.

If one reviews the faults which have occurred on supply undertakings during the last few years one finds that there have been very few serious busbar faults, and where such faults have occurred most of the damage has been caused by the fire which has ensued. If we adopt a sound method of sectionalizing, give duplicate supplies from different sections, and provide adequate fire-fighting appliances, we can for the time being neglect the risk of busbar faults; and the chances of a serious interruption of supply will be far less than would be incurred by the adoption of any of the existing methods. If undertakers indiscriminately adopt any of the systems which have been put before them they will be faced with far more interruptions caused by the mal-operation of protective gear than will be caused through the occurrence of busbar faults.

[The author's reply to this discussion will be published in a later issue of the *Journal*.]

## MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 15TH MARCH, 1937

**Mr. H. Hoyle:** It is generally agreed that the risk of fire with electrical equipment comes from the use of oil, and in all cases of fire it will be found that the oil, which is of an inflammable nature, is in contact with or in close proximity to the means of ignition, namely electrically-charged or heated metal surfaces.

In studying any system whereby a fire can be extinguished one must take into account the nature of oil fires. All such fires are gas fires, since liquid as such cannot burn—it must first be vaporized. The characteristics of such a conflagration are intense heat, dense smoke, and rapidity of propagation. The author makes mention of the water-spray system, and I should therefore like to explain how water can be used to extinguish oil fires. It is essential that the water should be discharged not in the form of a fine mist but in broken streams travelling at high velocity, which, on impact with the surface of the oil, cause it to become broken up into small globules. In this state a water film builds up around each oil globule to form a temporary oil-in-water emulsion, which will not burn. The great advantage of water apart from its emulsification properties is the cooling effect on steel structural work, etc., in the vicinity of the outbreak. On this account I must differ from the author, who states that for outdoor switchgear foam can be more effective. A very serious outbreak occurred a short time ago on outdoor switchgear, and owing to the intense heat from the flames the steel structural work about the plant involved became extremely hot. Foam was applied, but this disintegrated on coming into contact with the hot metal and a fine powder was distributed into the atmosphere, causing considerable interference with the operations of the brigade who had been called to combat the conflagration. It was at one time thought possible to extinguish oil fires by taking advantage of the tremendous cooling effect of water spray. A fine mist was discharged on to the oil in an endeavour to effect extinction, but no measure of success whatever was achieved until the principle of emulsification was discovered a few years ago.

It is feared in some quarters that to install fixed protection throughout the power station will be an expensive matter, but this need not be the case. The equipment can be installed for a fraction of 1 per cent of the capital cost of the plant which it is to protect.

**Mr. J. F. O'Neill:** I should like some statistical information about the frequency of fires in electric supply stations, together with particulars of the causes and the seats of origin of the outbreaks. I believe that such occurrences are very rare, and that even the suggested precautions cannot completely eliminate the fire risk.

The wholehearted adoption of the author's recommendations would make, inevitably, for increased cost of construction. It would be of interest to know what the magnitude of this increase would be for the average class of building in use in this country. In my opinion we can arrive at approximately the same point, along the road to complete fire prevention, by investing such additional outlay on more robust switchgear and plant. At the same time we could realize the inherent advantages of this superior apparatus in the directions of more reliable duty and simplified maintenance.

On page 294 the author recommends that the supply engineers should undertake the examination and inspec-

tion of fire appliances. Would not the local fire authority be a much more competent body to attend to such duties?

**Mr. H. Norris:** Has the author any details as to the behaviour of steelwork when sprayed with $\frac{3}{4}$ in. of asbestos? The Fire Offices Committee in certain of their Rules stipulate a covering of 2 in. of concrete for all steelwork.

**Mr. T. Hodge:** I believe many fires could be prevented if there were more frequent inspection of busbar and cable connections, and also if temperature alarms were installed. I suggest that a panel made of fine gauze, such as is used in miners' safety lamps, should be fitted at the bottom of each door to prevent oil igniting and so spreading the fire on the other side.

In regard to page 295, where the author says "The most violent and difficult type of oil fire to deal with is that in which the oil is first brought up to the flash point and then ignited," I once had some trouble with an oil-immersed starter and I dropped the tank to see whether the connections were in order. Eventually the coils began to get hot and to smoke, so I switched the starter off. The arc that followed set fire to the smoke, and in an instant there was a blaze the full width of the tank. Fortunately, I was able to smother it out with a piece of sacking.

[The author's reply to this discussion will be published in a later issue of the *Journal*.]

# APPLICATIONS AND CONSTRUCTION OF TRANSFORMER ON-LOAD TAP-CHANGING GEAR

By H. DIGGLE, B.Sc.Tech., Associate Member.

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SUMMARY

The paper deals briefly with the development of tap-changing gear and indicates some of the fields of application of tap-changing gear in power supply systems.

The various circuit diagrams in common use, and the types of tap-changing equipment, are classified, and brief descriptions are given of a number of typical equipments. The fundamental principles of methods of remote electrical and automatic control are indicated, and the effect of impulse voltages on the design of tap-changing gear is referred to.

The paper concludes with a brief section on economical types of voltage regulators for rural lines, and a section giving a statement of operating experience gained over a number of years, with some notes on earlier troubles and their remedies.

It is not within the scope of the paper to make comparisons between regulation by tap-changers and by other forms of regulator, as the paper is restricted to transformer tap-changing gear and its applications.

CONTENTS



## (1) INTRODUCTION

The use of tap-changing switches to vary the turns ratio of a transformer on load is not new, and faceplate switches similar to "end cell" battery switches were used at least 40 years ago. In the early years of this century, manually-operated and electrically-controlled types of these and other combinations of contactors or switches were applied to a limited extent for voltage regulation of feeders and control of reactive kVA in interconnectors between systems. A number of designs were developed in Europe and the U.S.A., but it was not until the years following the War that serious consideration was given to the design of apparatus suitable for large and high-voltage transformers, conforming to the practice of completely ironclad switchgear. Loading-gauge limitations in this country have had some influence on the design, but very large transformers can be transported by rail with the tap-changing gear in position.

The decision of the Central Electricity Board in 1928 to specify on-load tap-changing on all their 132-kV transformers presented a number of manufacturers with the problem of the design and manufacture of apparatus suitable for large and high-voltage transformers. Steady development has taken place subsequently in lowering the limit in transformer size to which tap-changing gear can be applied conveniently and economically, and in the applications of automatic and supervisory control.

In this paper the principal switching circuits are described and the essential principles of construction of a representative number of types of tap-changer are indicated.

## (2) FIELDS OF APPLICATION OF TAP-CHANGING GEAR

A number of papers have been published dealing with particular applications of regulators and tap-changing gear. Space does not permit of more than a summary of the principal applications, and references giving more complete information are quoted in the Bibliography.

### (a) Voltage Regulation of Feeders and Networks

Among the principal uses of tap-changing gear are the voltage regulation of a.c. systems, and of d.c. systems (by a switch on the primary side of the transformer feeding a rotary convertor or mercury-arc rectifier). It is not necessary here to deal with the bad effects on lamps and the loss of revenue on heating and lighting loads due to poor voltage regulation, as these have been dealt with in recent papers before the Institution.*

An undertaking which is dependent on a bulk supply has not the means of compensating for the voltage-drop in cables, etc., at peak-load periods by increasing the generator voltage, and the difficulties are increased by the domestic load having changed from a purely lighting load to a considerable power load. There are, broadly, two schools of thought on the application of voltage regulation to urban supply systems: (i) To apply the regulating means as near to the load as possible (which involves a large number of regulators). (ii) To apply the regulating means to a relatively small number of distribution points.

In Great Britain it is rare to apply a regulator nearer

* See Bibliography, (10) and (11).

to the load than the distribution transformer. In some systems "on-load" tap-changing on the primary side of distribution transformers has been standardized and, provided the transformer is not too small, this is the cheapest and most efficient method of providing voltage regulation on new transformers. Various forms of regulator are available for the control of individual low-voltage sections or of the output of existing transformers. Automatic control and line-drop compensation maintain the desired secondary voltages.

Examples of the second class are small undertakings receiving a bulk supply (in which case a regulator is put at the supply point), and the systems of some of the large cities, e.g. Manchester, where it has been necessary to superimpose a higher-voltage system, e.g. 33 kV, on the existing 6·6-kV system by supplying at the higher voltage to a limited number of main substations, where the voltage is reduced to 6·6 kV by transformers of 5 000 to 10 000 kVA. Sections of the original 6·6-kV network are supplied from two or more transformers,

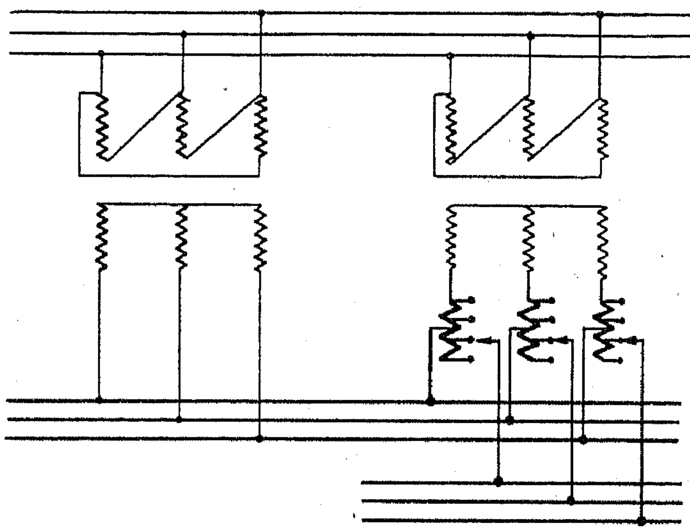


**Fig. 1.**—Addition of transformer with tap-changing gear.

which are not usually operated in parallel, in order to localize the area of any possible shutdowns and to keep down the fault kVA of the 6·6-kV switchgear. Tap-changers on the primary side of new main transformers or tap-changer boosters in series with the secondary windings of the older transformers, automatically controlled from relays connected across the 6·6-kV voltage transformers, maintain the voltage of 6·6 kV.

It has been shown in a recent paper* that, by selection of the "off-circuit" tappings of the distribution transformers in relation to the lengths and loadings of the 6·6-kV cables and by experiment with the line-drop compensator settings, reasonably good results have been achieved on the low-voltage system by regulating only at the 6·6-kV busbars in the main substation.

### (b) Application to Existing Transformers

When it is desired to add on-load voltage regulation to an existing transformer or group of transformers in a substation, it is usual to add some form of booster or auto-transformer regulator in series with the secondary windings; it is not generally possible without considerable expense and difficulty to add tap-changing gear directly to an existing transformer.

* See Bibliography, (9).

A system has recently been used in Germany (see Fig. 1) which avoids the use of boosters but involves an extra set of busbars. If the capacity of an existing transformer or group of transformers is to be increased and it is desired also to add on-load voltage regulation the new transformer is provided with a tapping section of sufficient sectional area to deal with the full-load current of two or more transformers as required, and thus, by the use of only one tap-changer, the output of a group of transformers can be regulated.* The system can, of course, only be applied if the transformers are operated in parallel.

Auto-transformer regulators call for little comment. When the current of the circuit permits of the use of tap-changing switches directly in the main circuit, an auto-transformer with tapped winding is generally to be preferred to a booster regulator.

Fig. 2(*a*) shows one of the booster schemes. An "exciting" transformer (which may be of either the double-wound or the auto-transformer type) is connected across the line and feeds variable voltage into a series-connected booster transformer, a tap-changing switch being used to select the amount of voltage which is injected into the primary of the booster transformer. (One point of the switching circuit is usually earthed if the exciting transformer is double-wound.) If the boost is to be equally positive and negative a centre tapping taken out of the "exciting" transformer secondary achieves the desired result at the expense of some "inactive" copper, one half of the winding only being used for maximum boost and the other half for maximum buck.

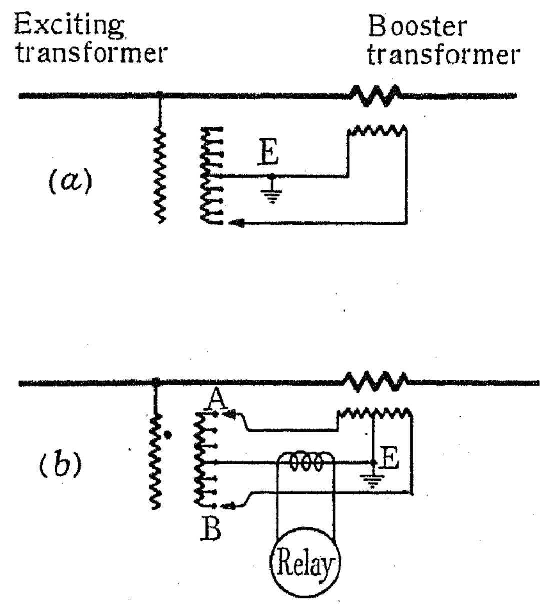



**Fig. 2.**—Exciter and booster transformer schemes.

One method of overcoming this drawback is to fit reversing switches across the primary of the booster transformer; this involves special switchgear. An alternative solution is shown in Fig. 2(*b*). The centre points of the "exciting" transformer winding and of the primary winding of the booster are permanently connected, and the two contacts of the tap-changer are arranged to move in opposite directions by the introduction of gearing. In all the running positions contacts A and B are equidistant from the centre tapping. At zero boost both are on the middle tap and, if the

* See Bibliography, (13).

switch positions shown in Fig. 2(*b*) give maximum boost, maximum buck is achieved when the positions are reversed. Current passes through the centre connection only during a tap-change, and energizes a protective relay whose contacts close if the normal time of a tap-change is exceeded.

Boosters are of particular use if a heavy-current circuit is involved as, by suitable choice of voltage in the switching circuit, the current to be dealt with by the tap-changer can be kept within reasonable limits.

### (c) Tap Starting of Large Motors

Standard on-load tap-changing gear has been used with advantage in tap-starting large synchronous motors, and a number of 20 000-kVA 10 000-volt synchronous condensers, fed from 40 000/10 000-volt transformers, have been started in this manner from tappings on the low-voltage side. The condenser is brought up to speed and synchronized on one of the lower tappings; the field switch is then closed, and the tap-changer run right through to the 100 per cent running tap. The oscillogram of Fig. 3 (see Plate, facing page 332) shows the voltage and current variations during the starting period.

The incorporation of the starting switchgear on the transformers saved the cost of the building space which would have been needed for the normal starting switchgear, as the transformers were of the outdoor type, and also saved the cost of cable connections between the transformers, machine, and switchgear.

### (d) Control of Power Factor in Interconnectors between two or more Systems Not Forming a Closed Loop

When two generating stations are operated in parallel and each has its busbar voltage fixed, some means of regulation is usually necessary to compensate for the voltage-drop of the cables and transformers in the interconnector. The amount of power and the direction of power flow between the two systems are determined by the governor settings of the prime movers, but the power factor cannot be controlled without some means of voltage regulation. This may take the form of a tap-changer on one of the transformers (if any), or of a booster in the interconnector. The conditions for short lines, where capacitance effects can be ignored, are illustrated in the well-known Mershon chart of Fig. 4. The resistance and reactance voltage-drops of the line and of any transformers, when added to the received voltage $E_1$, give the amount of the required sending voltage $E_2$. With equal voltages ($E_1 = E_2$) the only possible condition of load transfer is at a leading power factor. If leading reactive kVA is to be avoided, some form of regulator is necessary to provide the voltage-difference between $E_2$ and $E_1$, and by adjustment of the amount of boost the power factor can be controlled. This subject has been dealt with fully in a number of papers elsewhere.*

In the case of two systems an in-phase boost is all that is required, and there will be a phase displacement between the voltages of the two systems.

If three systems A, B, and C, are interconnected (A-B, B-C) but do not form a closed loop, the conditions are similar to those of two systems, and the power factor can be controlled by two single in-phase regulators, between A and B and between B and C respectively. A voltage and phase difference will exist between the station voltages.

* See Bibliography, (1), (2), (3), (4), (5), and (7).

### (e) Control of Load Distribution in Parallel Circuits

Sometimes it is necessary to operate in parallel two circuits of which the total resistances and reactances (of lines and any transformers) are not equal: for example, an overhead line, with or without step-up and step-down transformers, in parallel with an underground cable.

The conditions of parallel operation of two circuits of different resistance and reactance are shown in Fig. 5. The resistances and reactances of the two circuits are $R_1$, $R_2$, and $X_1$, $X_2$, respectively. If the ratios $R_1/X_1$ and $R_2/X_2$ are not equal, the relative phase positions of the currents $I_1$ and $I_2$ will be determined by their respective ratios $R/X$ and their magnitudes by the values of $R_1$, $R_2$, $X_1$, and $X_2$, as their impedance drops must be equal [see Fig. 5(*b*)]. In the conditions shown in the diagram the currents are out of phase and cannot be controlled. If $R_1$ and $R_2$, and $X_1$ and $X_2$, are not equal, and it is desired to be able to control and equalize the two currents and to bring them into phase, a boost must be introduced of the same magnitude and phase angle as the vector ($E_{2a} - E_{2b}$) of Fig. 5(*c*). Practical examples of these conditions have been published elsewhere.*

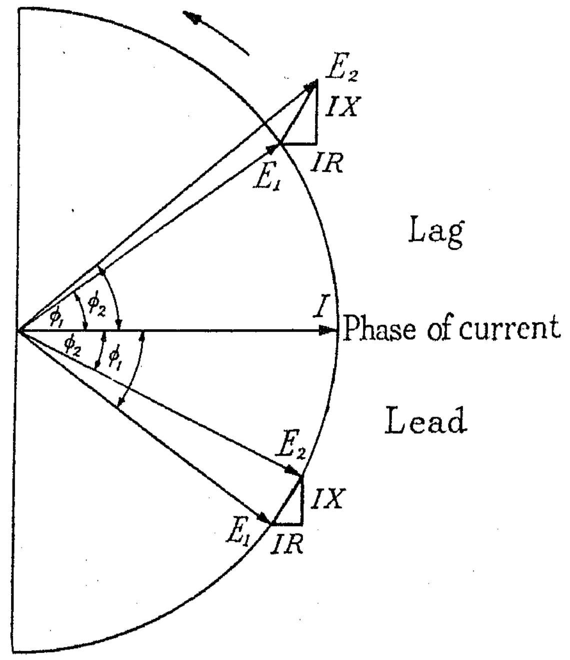



**Fig. 4.**—Interconnection between two systems.

$E_1$ = received voltage.
$E_2$ = sending voltage.
$I$ = current.
$IR$ = resistance drop.
$IX$ = reactance drop.
$\cos\phi_1$ = power factor (receiving end).
$\cos\phi_2$ = power factor (sending end).

A similar condition occurs if three (or more) systems are interconnected in a closed loop for load transfer. If the loop is broken at one point a voltage and phase difference will exist across the gap. If it is desired to close the gap and to control completely the flow of

* See Bibliography, (5), (7), and (8).

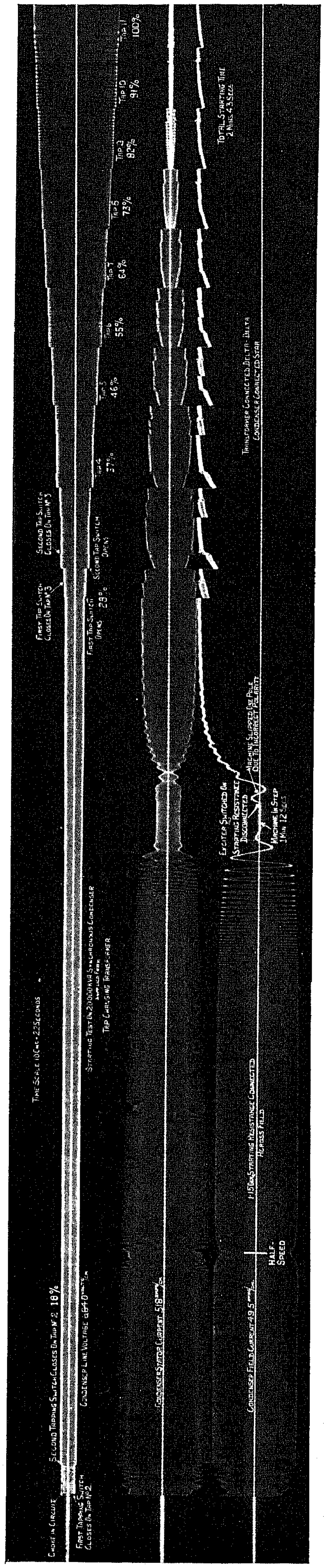


**Fig. 3.**—Oscillogram of starting conditions for tap-started 20 000-kVA synchronous condenser.

current round the loop it is similarly necessary to add boost at a definite angle, or separate in-phase and quadrature control, across the gap. These conditions can be met by means of transformers fitted with tap-changing gear.

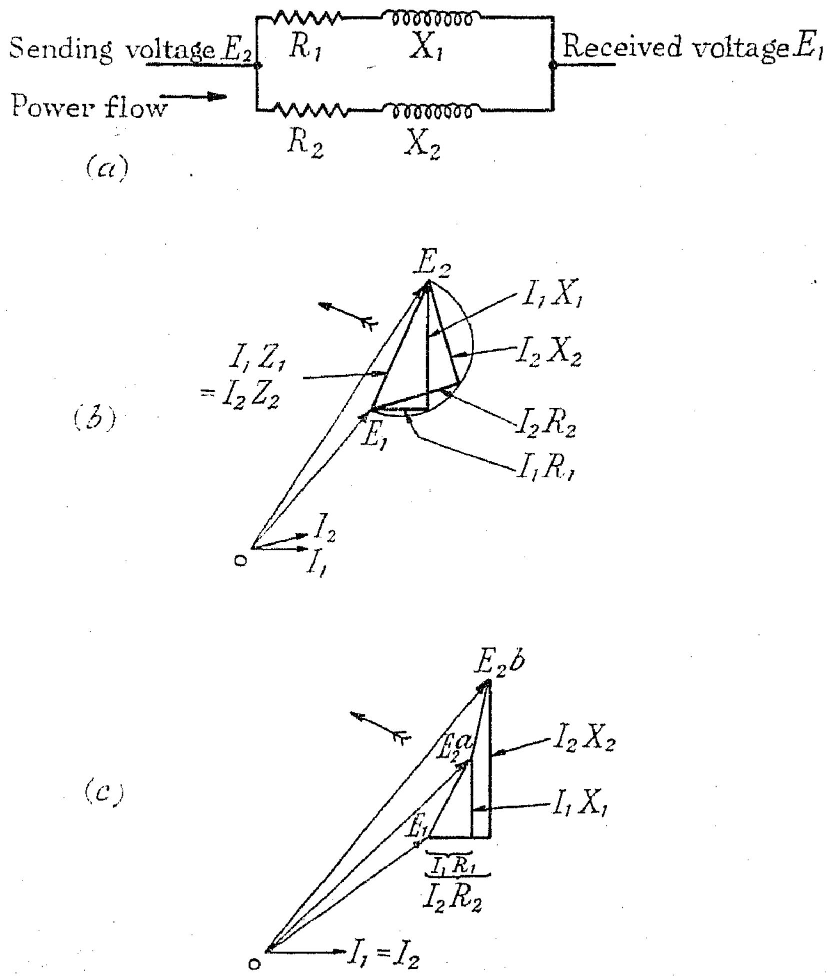



Fig. 5.—Control of current distribution in two parallel circuits (diagrams drawn for lagging power factor).

## (f) Production of In-Phase and Quadrature Boost

Boost at a variable angle can be added to a 3-phase system (Fig. 6), by combining boost A-$A_1$, B-$B_1$, and C-$C_1$ (in phase with the voltage) with boost A-$A_2$, B-$B_2$, and C-$C_2$ (in quadrature with the voltage). A 10 per

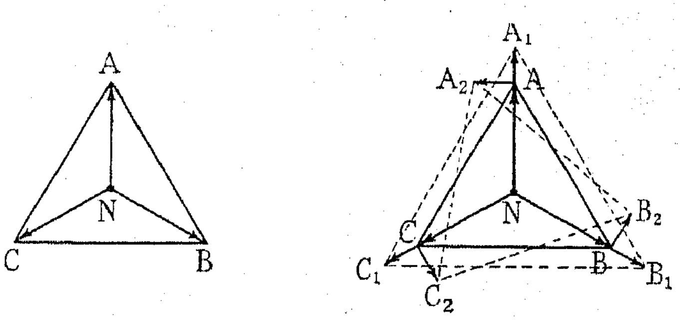



Fig. 6.—Production of "in-phase" and "quadrature" boost.

cent quadrature boost will give a phase swing of approximately 6°, 20 per cent 11°, and 36 per cent 20°.

One method of giving independent quadrature and in-phase boost which has been used in the U.S.A. employs an exciting transformer, connected delta/star, with two tap-changers feeding variable voltage to the primary windings of two booster transformers, which are connected star and delta respectively (see Fig. 7). The tap-changers work on a common tapped exciting winding but are independently operated. The voltage induced in the secondary side of the star-connected booster is in quadrature with the "phase voltage" (see vector diagrams at foot of Fig. 7). This system, although

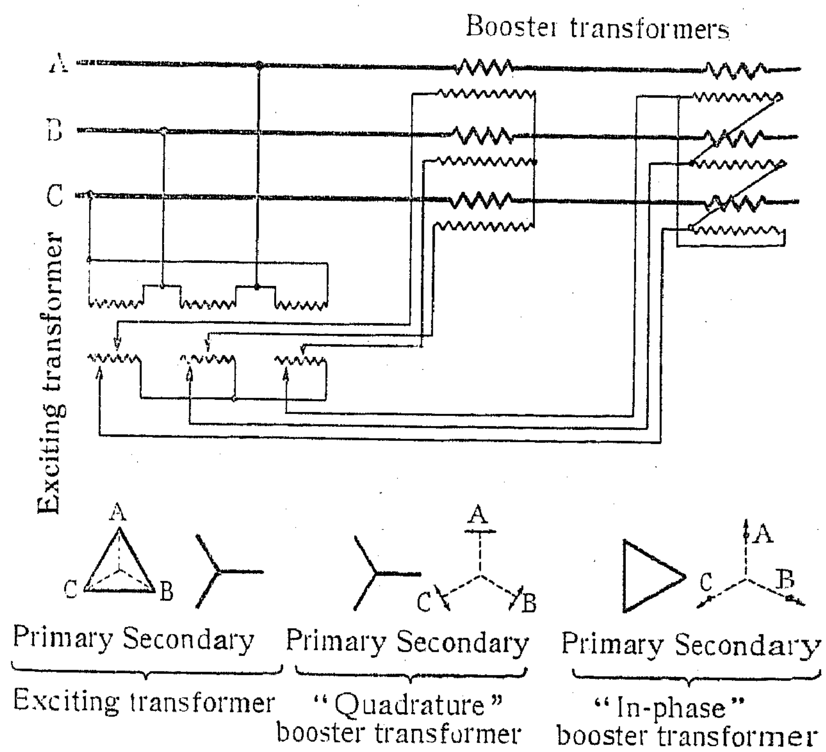



Fig. 7.—Production of "in-phase" and "quadrature" boost by two booster transformers.

completely flexible, is expensive owing to the duplicate sets of boosters and the motor-operated tap-changers and their controls, and numerous efforts have been made to achieve the desired result by cheaper means.

For cases where the voltage and current are such that they can be handled by standard tap-changing switches, alternative arrangements have been devised which reduce the number of transformers to two or even to one, but they all require the use of two independent tap-changers. Although such arrangements have had a limited application in the U.S.A. they do not appear likely to become common owing to the necessarily high cost.

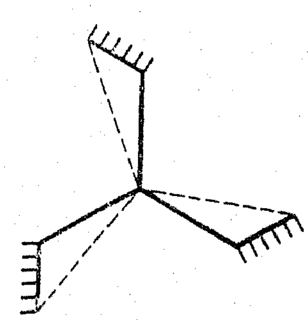


Fig. 8.—Inter-star connection.

Complete flexibility of the quadrature component is not always necessary, and schemes have been devised to produce boost at a definite angle. One of these uses a hexagon connection with "overhanging" windings. By choice of the numbers of turns in the adjacent sides of the hexagon, and of the phase connections of the "overhung" windings, the phase angle of the boost can be varied between limits of 0° and 90°.

Frequently positive phase-shift and positive boost are required simultaneously, and a fair approximation to the desired conditions can be achieved by the inter-star connection (Fig. 8), which adds boost at a fixed angle of 60° to the phase voltage and uses only one tap-changer. Several schemes using this connection have been put into practice, and a discussion on the effect of adding boost on these lines is given elsewhere.*

### (3) CIRCUITS USED FOR ON-LOAD TAP-CHANGING

All forms of on-load tap-changing circuits exhibit two fundamental features: (*a*) some form of impedance is introduced to prevent short-circuiting of tappings; (*b*) a duplicate circuit is provided so that the load can be carried by one circuit whilst switching is being done on the other, and the main circuit is not opened during a tap-change.

The exact form taken by the circuit varies considerably, but these principles will be apparent in all the circuits described in this paper.

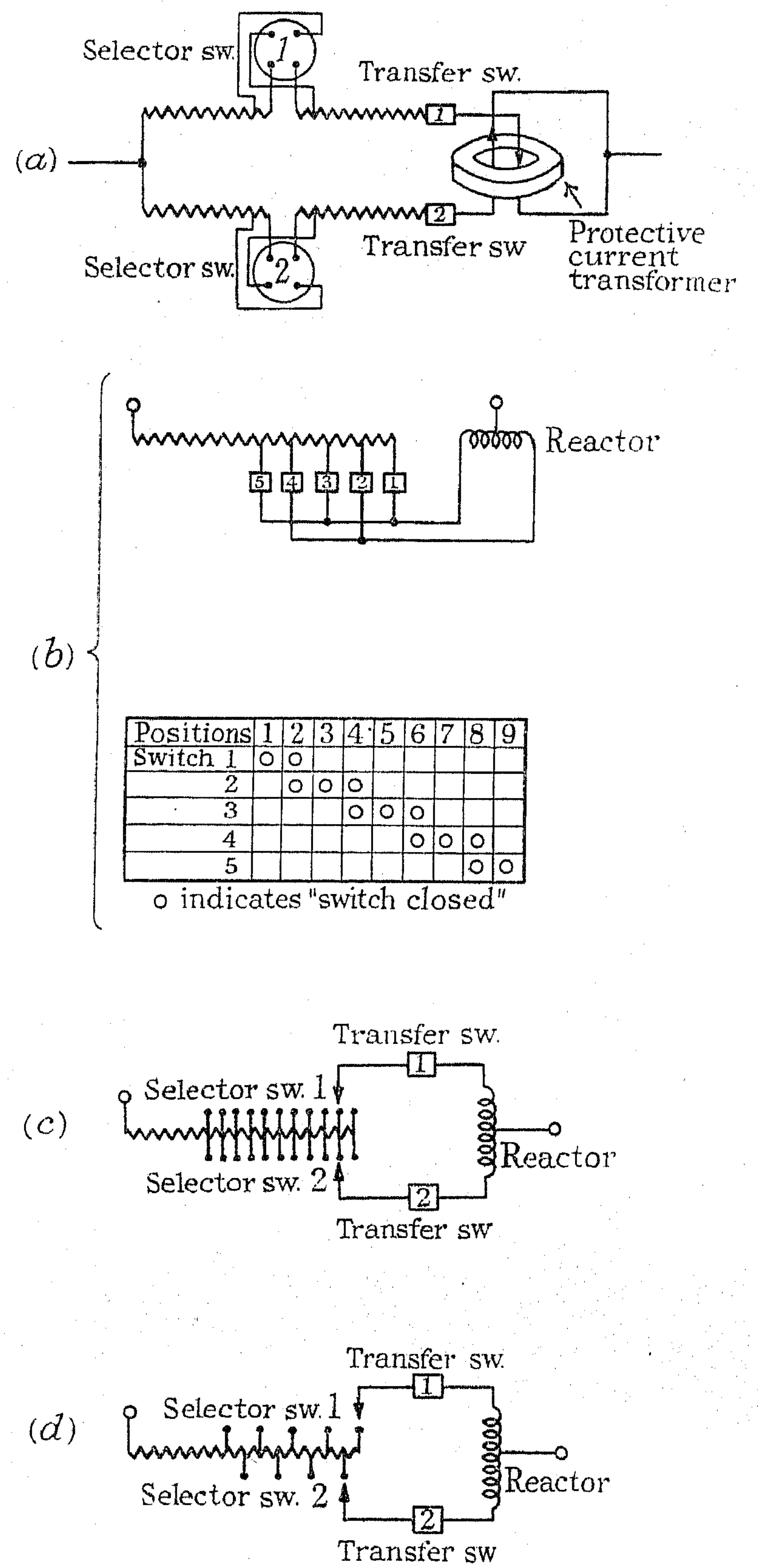
#### (a) Parallel-Winding Circuits

A development from the operation of two transformers in parallel is to provide two circuits for one of the main windings of the transformer [Fig. 9(*a*)]. Each has a tapping selector switch and a transfer switch, and normal operation is with the two windings connected to the same tap and in parallel. The operation of changing taps involves six switching operations. Transfer switch No. 1 is opened, thus throwing all the load on to No. 2 winding. Selector switch No. 1 is moved one position, and then No. 1 transfer switch is closed, thus temporarily paralleling the two windings on unequal taps. A similar series of operations on No. 2 circuit completes the tap-change movement on both windings. This scheme was originally developed in the U.S.A., and has had a limited application in this country.

The design of the windings involves a compromise. High reactance is desired between the halves of the winding to limit circulating currents when on unequal tappings, but the reactance between one half-winding and the other main winding (i.e. primary or secondary) must not differ by much from the reactance between the two half-windings (when connected in parallel) and the other main winding, in order to avoid a high reactive drop and consequent fall in voltage when the load is carried only by one half-winding. These conditions are rather contradictory, and a compromise has to be made which does not involve heavy circulating currents or wide voltage variations during a tap-change.

As each half-winding has to carry 100 per cent overload temporarily, if the transformer is on full load, protective gear is necessary to guard against an incomplete movement of the tap-changer. This usually takes the form of a ring-type current transformer. The currents of the two primary conductors flow in opposite directions, so that voltage is induced in the secondary winding only when the primary currents differ, i.e. during a tap-change, and the transformer is tripped out if a tap-change is not completed. Objections have been raised to the principle of overloading which this method involves, and the consequent risk of interruption of the supply if the tap-changer fails to complete an operation. Other methods have been developed which are not subject to these objections.

* See Bibliography, (7).




| Positions | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Switch 1 | o | o | | | | | | | |
| 2 | | o | o | o | | | | | |
| 3 | | | | o | o | o | | | |
| 4 | | | | | | o | o | o | |
| 5 | | | | | | | | o | o |

**Fig. 9.**—Parallel- and single-winding schemes.

#### (b) Single-Winding Circuits with Duplicate Selector Switches

An alternative circuit, which also originated in the U.S.A., is shown in Fig. 9(*b*). In this case only a single winding is used, and a current-breaking switch is connected to each transformer tapping. Alternate switches are connected together to form two common groups which are connected to the outer terminals of a mid-

point auto-transformer or reactor, whose windings are designed to carry full-load current continuously. The sequence of changing of taps is indicated by the table in Fig. 9(*b*). In the first position, switch No. 1 is closed and the circuit is completed through half the reactor winding. To change taps one position, No. 2 switch is closed in addition to No. 1. The reactor then bridges a winding section between two taps and gives a voltage midway between the two taps. For the next tap-change No. 1 switch is opened and No. 2 left closed. Circuit is then completed to the second main winding tap through half the reactor winding. The main transformer or reactor windings are not overloaded and no protective gear is required to guard against incomplete operation.

The sequence of changing of taps involves closing one switch or two adjacent switches alternately. Owing to half the reactor winding being in circuit on adjacent taps unequal voltage-steps result, and sometimes a short-circuiting switch for the reactor is added, but this is done only at the expense of simplicity in the operating mechanism.

This circuit involves large dimensions and oil quantity for the tap-changer if a large number of taps are required, particularly if the equipment is to be 3-phase, and the natural development from this circuit is to convert the two groups of current-breaking switches into two selector switches with transfer or series switches in the common leads to the reactor [Fig. 9(*c*)]. This retains the advantages of the single-winding circuit (i.e. no overloading of windings, etc.) and the relative movement of the switches to change taps is similar to that described for the parallel-winding system, i.e. six movements to change one step, both selector switches being connected to the same tapping and both transfer switches closed in all running positions.

With this arrangement the maximum number of voltage positions is restricted to the number of available contacts in the selector switch. If a greater number of taps is required, either the circuit of Fig. 9(*c*) can be retained and the movement of the switch arrested half way through a complete tap-change, i.e. the centre tap of the reactor is utilized as a running tap, or the connections can be arranged as shown in Fig. 9(*d*). In this case the tapping connections to the two selector switches are " staggered," and in all the full running positions one transfer switch only is closed and half the reactor winding is in circuit on all tappings. This arrangement has the advantage that the reactor is never left connected across a winding section and so does not add to the open-circuit loss of the transformer in any of the positions, and the voltage steps are equal.

The use of the mid-point reactor causes a non-uniform voltage variation in changing from one step to the next, but this is of no practical importance if the steps are sufficiently small, e.g. $1\frac{1}{2}$ per cent. The conditions of the winding connections during a tap-change are shown in Figs. 10(*a*) to 10(*e*). The voltage in position (*c*) is midway between those of the two taps, but in positions (*b*) and (*d*) reactive drop is introduced by half the reactor winding. The magnitude of this drop is proportional to the inductance of the reactor, which is designed to be fairly small. Again a compromise has to be effected as, if the inductance is made very small so as to give low reactive drop with the half-winding in circuit, too great a magnetizing current will be taken when the reactor bridges a pair of adjacent tappings. Usually the current drawn from the tapping section under these conditions is about 50–60 per cent of full-load current; the conditions of voltage variation in changing tappings are shown in Fig. 10 for full-load current at 0·80 power factor lagging and for a reactor designed to draw 60 per

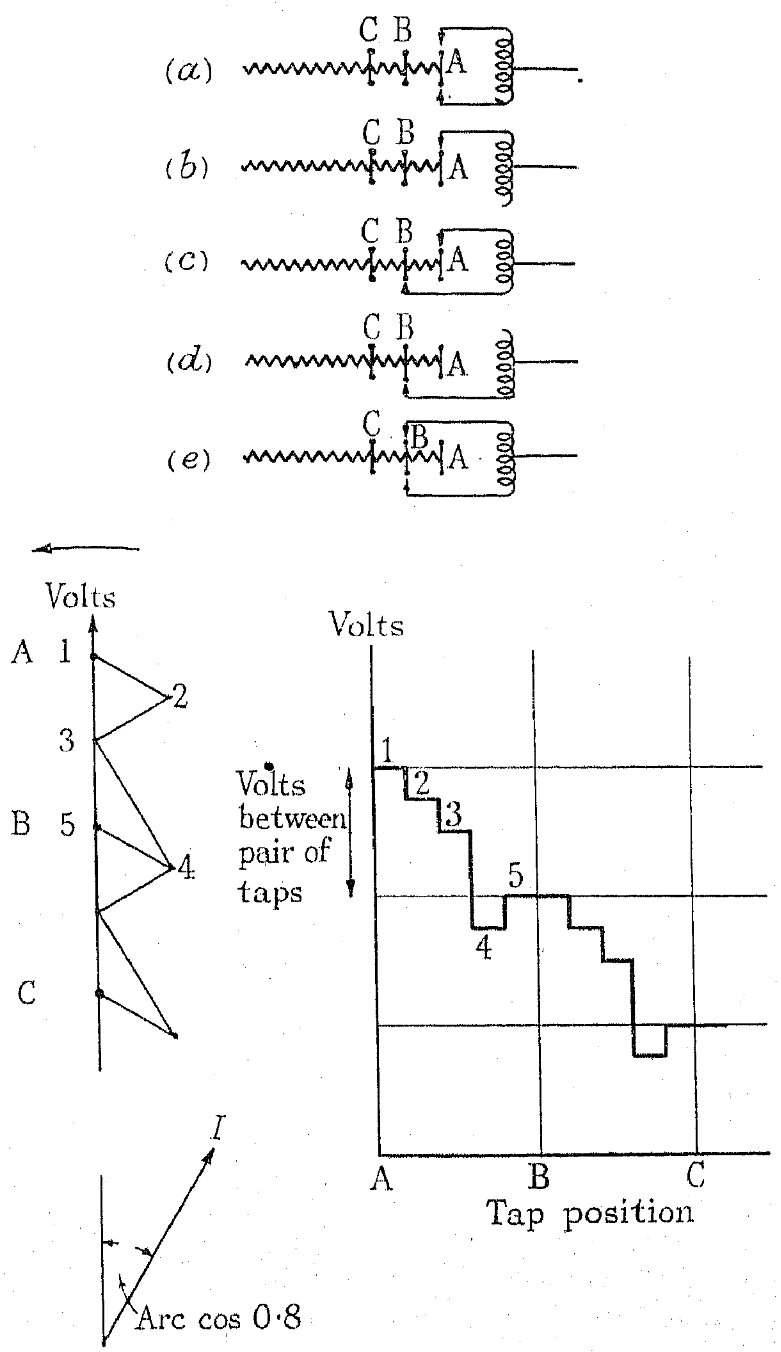



**Fig. 10.**—Voltage variation during a tap-change (diagrams drawn for power factor 0·8 lagging).

cent of full-load current in the bridging position. In moving in the direction to reduce the voltage, the voltage drops outside the range of " voltage of one step " by about 25 per cent in position (*d*) of Fig. 10. This corresponds to position (4) of the vector diagram.

For currents sufficiently small to enable the transfer or series switches to be dispensed with, the circuit reduces to that of Fig. 10, in which the current can be broken and made on the selector-switch contacts. This type is generally operated by some form of stored energy, and registering means are provided to ensure that a tap-change movement, once started, is definitely

completed and the moving and fixed contacts correctly registered. Mechanical interlocks ensure that one contact completes its movement before the other starts to move.

The same circuit can be used with a preventive resistor instead of a reactor, as shown in Fig. 11(*a*). In all the full running positions the resistor is short-circuited. One moving contact "makes" before the other "breaks." A special form of 3-phase switch of this type [Fig. 11(*b*)], in combination with a reversing switch which is mounted inside the outer ring of contacts, enables positive and negative boost to be obtained from a tapped auto-transformer. The connections of the reversing switch and its time of operation are so arranged that change from "buck" to "boost" is made without opening circuit. The main moving contact arms travel over the "track" of two phases for positions of buck and boost, but the 3-phase polarity of the main leads is not affected.

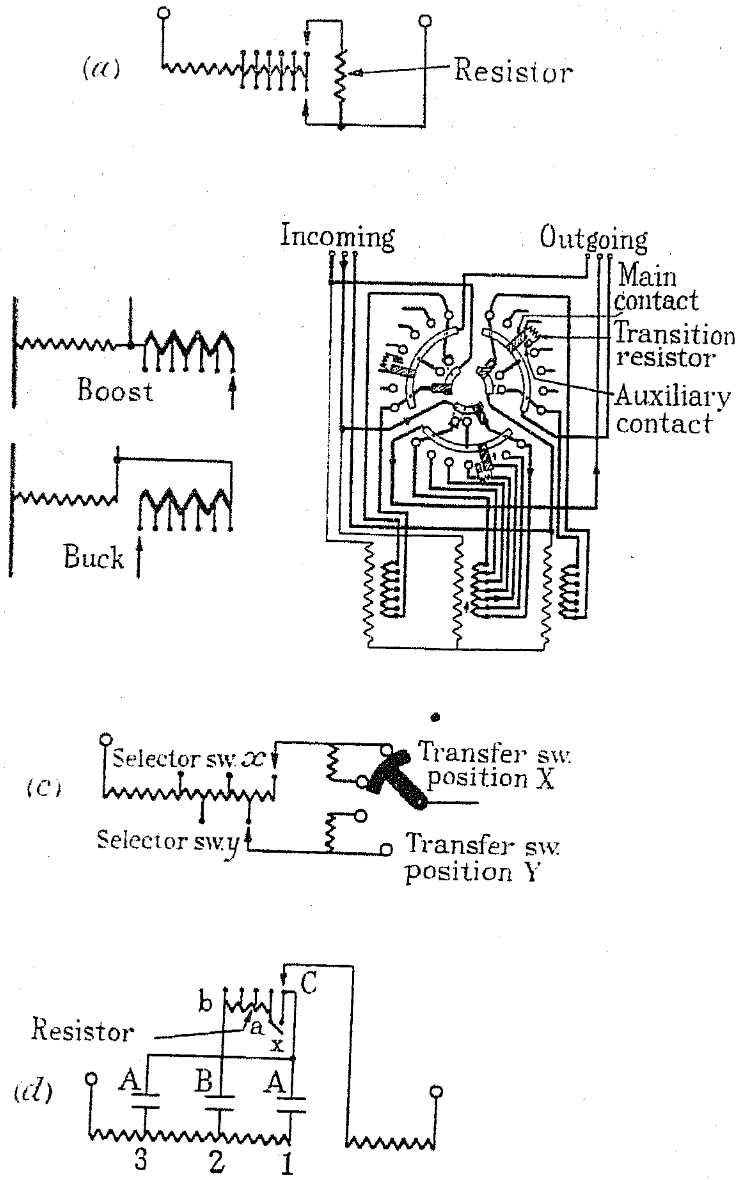



**Fig. 11.**—Single-winding schemes with "transition" resistor.

The use of resistors in place of reactors for the "transition" impedance was originally adopted only for relatively small equipments, but one advantage which is claimed, namely that the circuit which has to be broken is non-inductive so that less relative wear is to be expected on the switch contacts, has been partly responsible for the extension of the principle to larger equipments which involve the use of separate transfer switches. As the resistors cannot be left continuously in circuit the switches have to be operated by some form of stored energy to ensure definite and complete switch movement.

One form of circuit which is used for this purpose is shown in Fig. 11(*c*). "Staggered" tappings are taken to a pair of independently-operated selector switches and the transfer switch is caused to oscillate between two positions by stored energy. Four fixed contacts are connected to a pair of resistors. In the position shown, one selector switch is joined to one tapping and the other to an adjacent one. The circuit is completed through one short-circuited resistor and the transfer switch in position X. To change taps, the transfer switch is rapidly moved to the opposite position Y and selector switch $x$ is then moved to the next position in readiness for the next tap-change. The transfer-switch movement first removes the short-circuit from the resistor and later bridges the two resistors in series across the pair of tappings. It then completes circuit to the next tap through the second resistor, and finally short-circuits the latter.

In order to obtain a more smooth voltage-change from one tapping position to the next, one manufacturer has introduced tappings on the "transition" resistor [see Fig. 11(*d*)]. The main tappings are "staggered" and are connected to two groups of selector switches, A and B. A separate switch contact C operates on tappings on the resistor $ab$. In normal operation on tapping No. 1, contact 1A is closed and contact C makes direct contact to the tapping. Contact 2B is already closed and, to change taps, switch $x$ is closed and connects the resistor across the two tappings. Contact C is then rapidly moved over to contact $b$ and circuit is completed to tapping No. 2. Switch $x$ is then opened to disconnect the resistor. The completion of a switching operation is ensured by the use of stored energy.

One of the earliest forms of tap-changing gear was incorporated in the provision of a variable-voltage supply to high-voltage testing transformers, where, in order to obtain smooth voltage variation, an induction regulator was used to bridge between adjacent tappings. This principle has been revived and used in apparatus for tap-changing on large transformers. In the author's opinion it is doubtful whether these attempts at production of smooth voltage variation are justified under normal conditions, as no objectionable voltage-change or system disturbance results from the operation of a tap-changer using simple resistances or reactors if reasonably small tappings are used, and smooth variation is only obtained at the expense of considerable increase in volume and oil quantity.

The scheme adopted by one British manufacturer is shown in Fig. 12. I and II represent the stator winding, and III the rotor winding, of an induction regulator which is capable of movement to effective positions C′ to C″. Connections are made through two selector switches and "staggered" tappings on the transformer winding With the rotor in position C′, the point C is substantially at the potential of point A on the stator winding, i.e. of tapping No. 1, and a short-circuiting switch (not shown) between A and C can be closed. To

change the tapping position, the short-circuiting switch is opened and the rotor moved over to the position C″, when the point C is substantially at the potential of the next tapping (No. 2) and the short-circuiting switch (not shown) between C and B can be closed. Before the gear comes to rest, selector switch A moves to tap No. 3 in readiness for the next change.

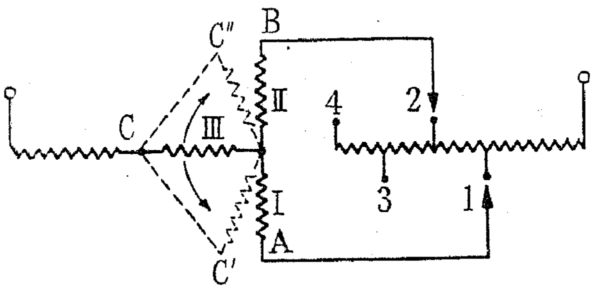



**Fig. 12.**—Single-winding scheme with induction regulator.

Most of the above circuits have been applied to oil-immersed switchgear for use on high-voltage circuits, and the principles of construction of some of the mechanisms are dealt with in Section (4).

## (4) PRINCIPLES OF CONSTRUCTION AND CLASSIFICATION OF DESIGNS OF TAP-CHANGING GEAR

### (a) Switches Driven Directly by Motor and Gearing

In the larger equipments, where duplicate selector and transfer switches have to be operated in a definite sequence, the respective operating shafts are usually mechanically interlocked by gearing which includes some form of geneva gear wheel for the operation of the selector switches, and cams for the operation of the transfer switches. The motor is directly coupled to the mechanism so that movement is arrested if the motor stops.

### (b) Switches Operated by Stored Energy

For the lower ratings where separate transfer switches can be eliminated, e.g. the circuits of Figs. 10, 11(*a*), 11(*b*), and 11(*d*), the tap-changer is frequently made in the form of a rotary switch which is operated through a multi-toothed geneva wheel, and completion of the switch movement is assured by stored energy in one of four forms: (i) Springs. (ii) Falling weight. (iii) Flywheel. (iv) Spring-loaded solenoids.

An example of a spring-loaded quick-acting mechanism, which uses a geneva gear drive to the switch shaft, is shown in Fig. 13. Loose travel is provided between the driving shaft A and the operator wheel E of the geneva gear, so that quick action is possible when the spring is extended. A loose intermediate driving disc B has a projection *b* which engages with the faces *a* on the main shaft A. Other faces *c* of the disc B engage with a projection *d* on the operator wheel E. When shaft A is revolved, the loose travel is taken up and disc B revolved. The spring is extended, and when "top dead centre" is passed the spring is released to operate E rapidly and so turn the geneva gear one tooth pitch. If the spring fails, the mechanism still operates but without quick-break action, and is reversible at any point of the travel.

The falling-weight design is based on the same principles, except that an offset weight is wound up, instead of a spring.

In the third type the motor is coupled directly to a flywheel. As it is brought up to speed a centrifugally-operated device couples the tap-changer shaft to the flywheel and, after the shaft has been turned by the amount of one tap-change, the flywheel is uncoupled and the motor allowed to come to rest.

Solenoids with ratchet mechanism are sometimes used in place of a motor drive, and an example of this arrangement is shown later in this section.

Provided the springs are liberally designed, it is rather a matter of opinion which of the first two types is to be preferred, and one firm at least uses both types. Reliable examples of all four types are manufactured, but, in the author's opinion, the flywheel scheme has one disadvantage, namely that it is only of use when the switch is operated electrically. The other types ensure prompt

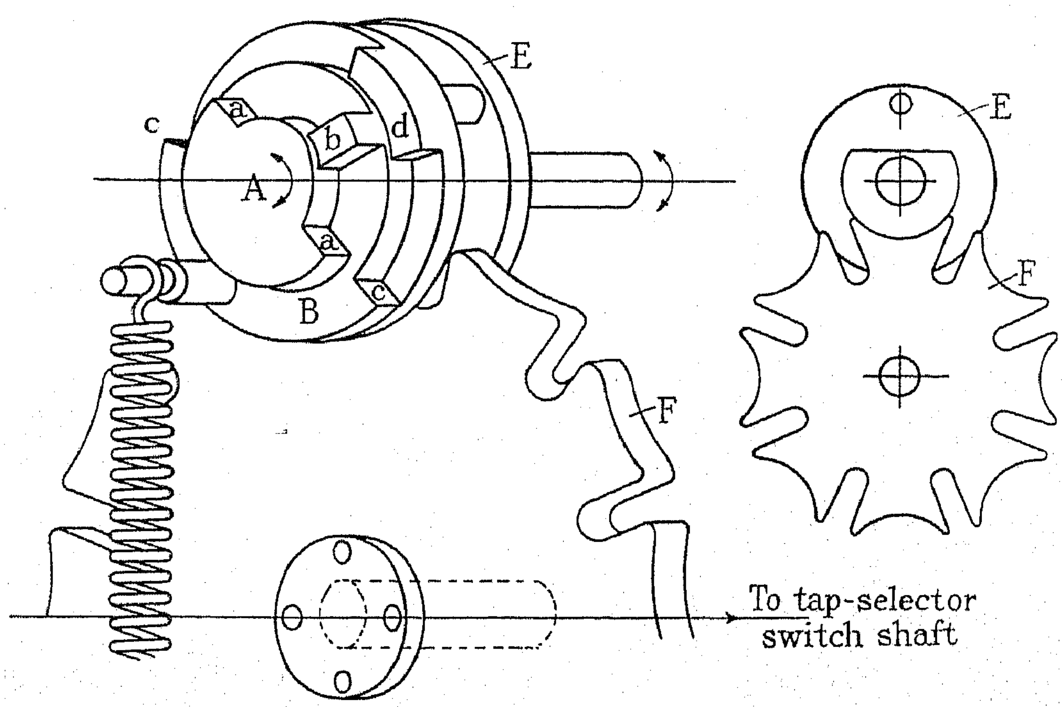



**Fig. 13.**—Spring-loaded quick-acting mechanism.

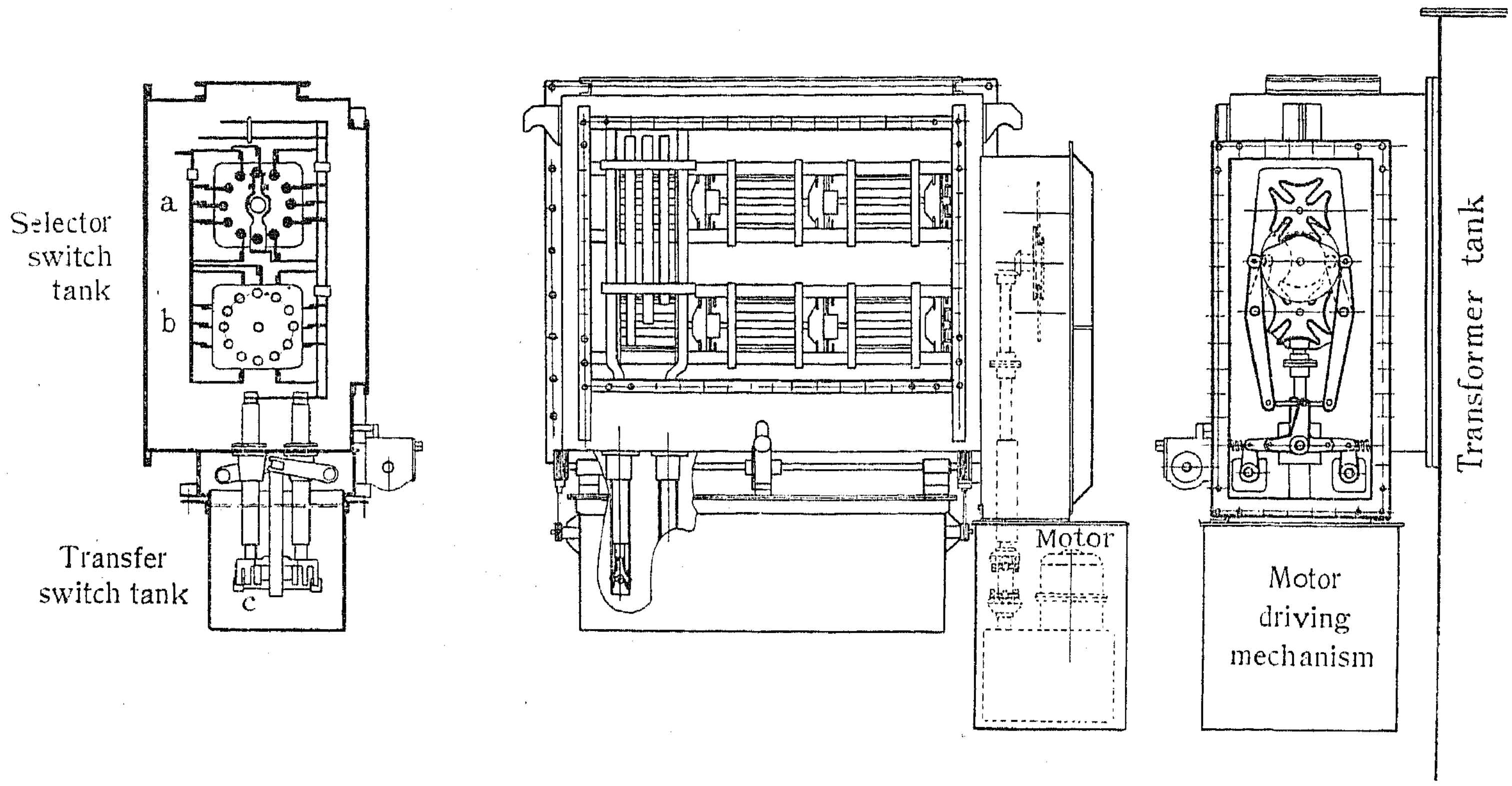



**Fig. 14.**—Tap-changer for large transformers using duplicate selector switches and transfer switches.

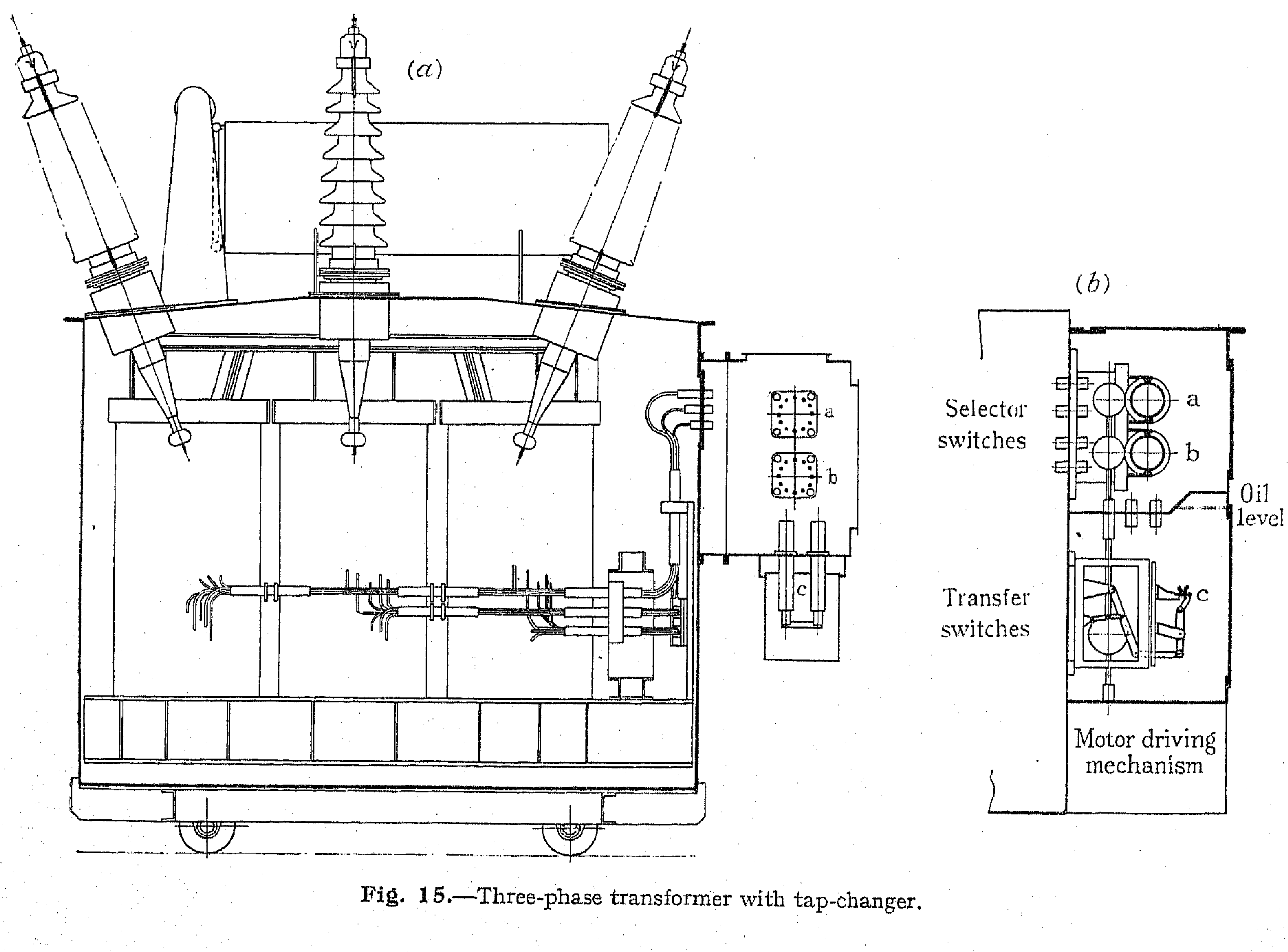



**Fig. 15.**—Three-phase transformer with tap-changer.

and complete switch movement whether operated directly by hand or electrically.

### (c) Typical Constructions of Tap-Changers

Owing to limitations of space it is only possible to indicate the essential features of a limited number of designs, of which the following are among the many alternatives.

**(i) Single-winding type with bridging reactor, and parallel-winding type with directly-driven tap-changer.**

The circuit of Fig. 9(*b*), in which a large number of contactors or switches are connected to the tappings, occupies a large volume if there are many tappings and has been largely superseded by designs using duplicate transfer and selector switches [see Figs.9(*c*) and 9(*d*)]. An example of the latter type, which is built as a separate unit, is shown in Fig. 14. There are three oil-filled compartments. In the larger compartment three pairs of rotary-type tap-selector switches are mounted in two rows with insulating couplings between switches, and the two spindles extend into the right-hand compartment, where they are coupled through a pair of geneva gear wheels to a central operating shaft; this includes cams for the operation of the transfer-switch spindles through a lever system. The latter includes toggle links to ensure quick-break action irrespective of the speed of the main shaft. The transfer switches, which are the only ones which make and break current, are mounted in the lower compartment whose tank can be lowered for inspection without draining oil. The main vertical shaft is coupled to the motor through reduction gearing, and one turn completes the switching movement of both selector and transfer switches by one tap position.

The application of this design to a large transformer is shown in Fig. 15(*a*). The mid-point reactor is mounted inside the transformer tank, and the tap-changer is mounted on the short end of the tank to permit transport by rail with the tap-changer and motor drive in position.

Another manufacturer's design of equivalent apparatus is shown in Fig. 15(*b*). In both cases the duplicate selector switches are marked "*a*" and "*b*" and the transfer switches "*c*." The design of Fig. 15(*b*) is similar to that of Fig. 15(*a*) in relation to the transformer, i.e. the tap-changer is on the short end of the transformer tank, but the switch parts are assembled in compartments of the main tank, to which access is gained by draining oil and unbolting cover plates. Cam-operated contactor-type transfer switches in the middle compartment are coupled to drum-controller type selector switches in the top compartment, and to the motor driving mechanism at the bottom.

**(ii) Single-winding type with "stored-energy"-operated tap-changer and bridging resistor (large type).**

One circuit for this type is shown in Fig. 11(*c*), and the design of a prominent German manufacturer is shown in Fig. 16. This indicates clearly the difference between British and (some forms of) Continental practice. All the British designs for high voltages are completely oil-immersed and ironclad. In the German design the duplicate selector switches *a* and *b*, which include geneva gear wheels, are mounted above the top yoke of the transformer. The vertical operating shafts of the selector switches are coupled by worm gears to a horizontal shaft which is connected through bevel gears to the motor drive at floor level. The three vertical selector-switch shafts are carried through bushings in the main cover, and the transfer switches, resistors, and spring-loaded mechanism of each phase are mounted in a tank at the top of each bushing. The tank is made "alive" and has to be drained for inspection of the switch parts.

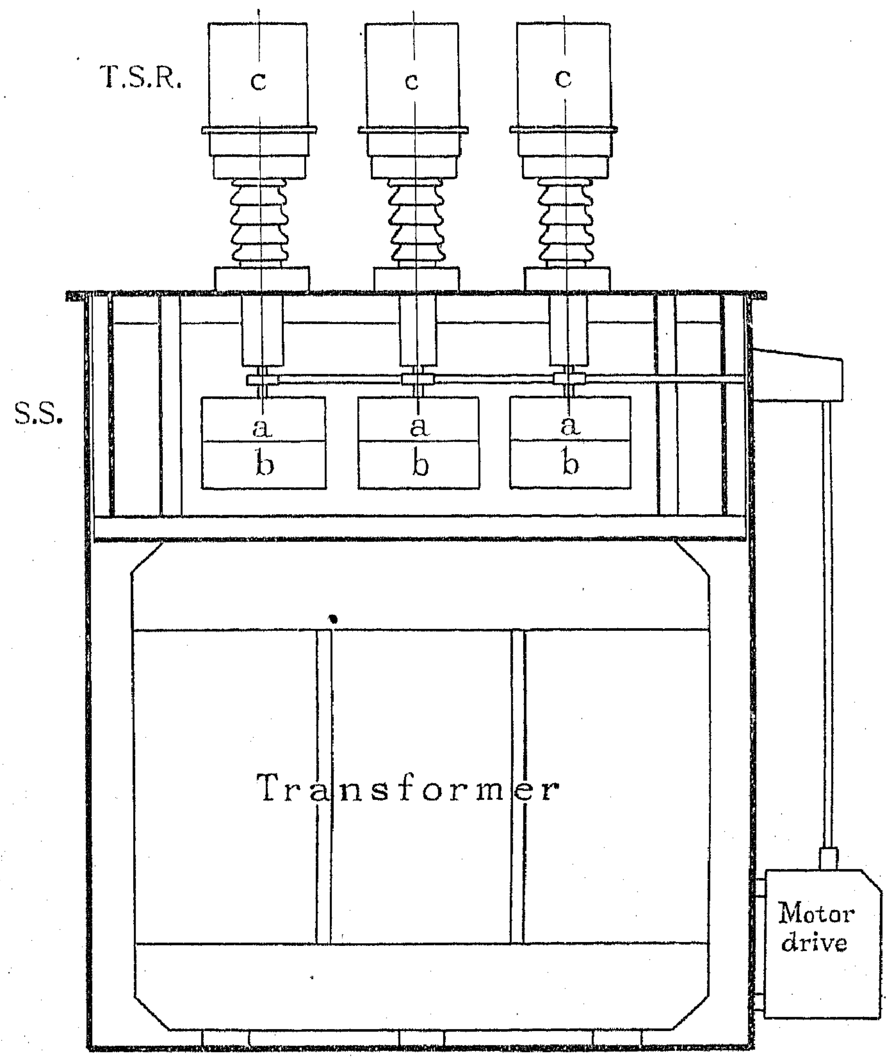



**Fig. 16.**—Three-phase transformer with "stored energy" type of tap-changer and using transition resistors.
S.S. = Selector switches.
T.S.R. = Transfer switches and resistors.

**(iii) Single-winding type with "stored-energy"-operated tap-changer and bridging resistor (small type).**

The circuit for this type is shown in Fig. 11(*a*), and one form of 3-phase switch is shown in Fig. 17. The tap-changer is mounted on a shelf outside the main tank and is enclosed in a smaller tank which can be hinged down after the oil has been removed.

The switch parts are assembled inside an insulating cylinder, which is made in two parts, of which one is removable for inspection. A series of double-bladed fixed contacts engage with two moving contacts, which are so offset that one makes contact with the next position before the other breaks contact. The preven-

tive resistor is connected between the two moving contacts, which receive definite step motion by means of a spring-loaded mechanism of the type indicated in Fig. 13. This is mounted above the switch spindle and coupled to the motor through gearing.

**(iv) Single-winding type with mercury switches and bridging reactor.**

This type employs the circuit of Fig. 9(*b*) and uses "mercury in glass" switches which make and break contact when tilted. This type is generally limited to fairly small transformers, and one form of construction is shown in Fig. 18. A 3-phase switch is shown mounted in a small compartment in the end of the transformer tank, and, as all the current making and breaking takes place inside the glass casings, no oiltight barrier is necessary in the tank wall. The switches are pivoted on panels of insulating board which are mounted radially in a framework. The switches of the three phases are linked together and are tilted in the required sequence by a double-sided cam which is attached to the bottom of the vertical driving spindle. The latter is coupled to the motor drive above the switch tank. As very little force is required to operate the switches, some makers use an "induction disc" motor which is immersed in the oil.

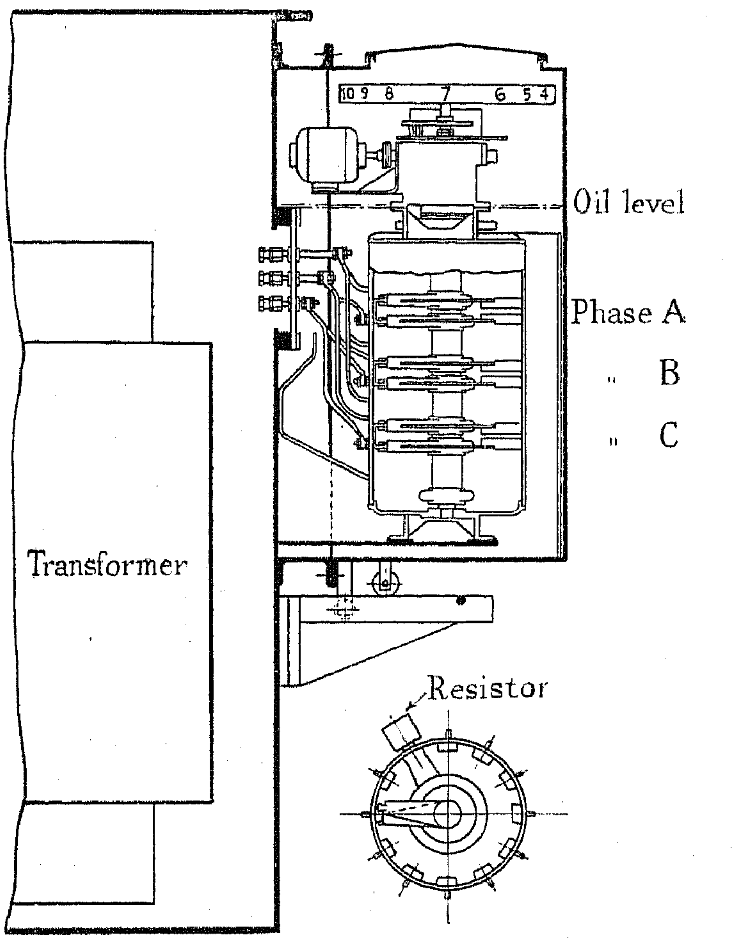



**Fig. 17.**—" Stored energy " type of 3-phase tap-changer using transition resistor.

## (d) Driving Mechanisms

**(i) Motor driving mechanisms.**

The main functions of a motor driving mechanism are: (1) to provide a driving torque of suitable magnitude and at a suitable speed on the main driving shaft of the tap-changer, (2) to ensure that the apparatus runs automatically for the distance of one complete tap-change whenever it has been started, (3) to ensure by limit switches and other safeguards (preferably of the mechanical type) that the normal range of travel is never exceeded, (4) to provide position indication by mechanical means at the tap-changer and at the control point by an electrical position indicator, (5) to provide a record of the number of tap-changes which have taken place, (6) to provide visual and/or audible signals when a tap-change is in progress, and (7) to provide easy and safe means of emergency operation by hand.

The essential parts of a mechanism which meets these conditions are shown in Fig. 19. This arrangement is particularly applicable to a tap-changer of the type using duplicate selector switches and transfer switches.

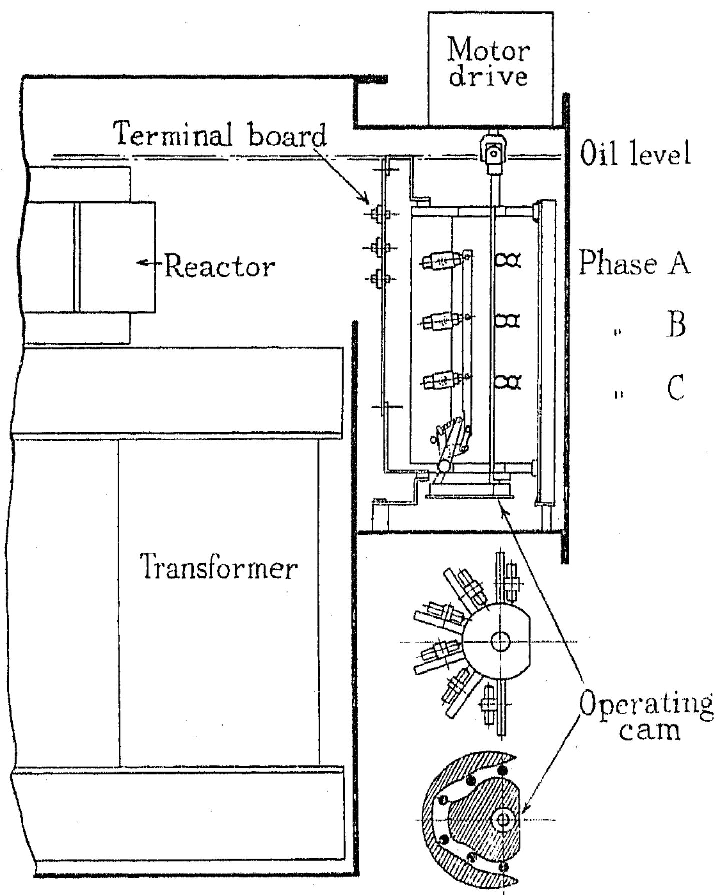



**Fig. 18.**—Three-phase tap-changer using mercury switches.

The vertical motor (M) is coupled through double worm reduction gears to the output shaft, which is connected to the tap-changer main driving shaft at O. One turn of the latter shaft gives a complete tap-change, and to ensure that the motor runs automatically for the distance of one tap-change when started up, auxiliary contacts 55 and 55A have their periods of making contact controlled by drum segments which are mounted on the main shaft. Contact 55 is open when the tap-changer is at rest, closes as soon as the gear moves, and opens again when one turn, i.e. a complete tap-change, has been completed. The closing of contact 55 operates on the coil of a contactor (which is energized to run the motor) and provides a hold-in circuit until 55 is opened again. Contact 55A operates in the reverse way to 55, i.e. it is closed when the gear is at rest, opens as

soon as the gear moves, and recloses when one revolution has been completed. It is generally used only when the tap-changer is automatically controlled, and its function is described later. A duplicate contact to 55 can be used to energize " tap-change in progress " signal lamps and/or alarms. A cyclometer counter (not shown) can be operated by a cam off the same shaft. To operate the limit switches, mechanical position indicator, and transmitter, of an electrical position indicator, a shaft is required which moves less than one complete revolution for the movement of the tap-changer over the whole tapping range. This is provided by the geneva gear, and the limit switches consist of contacts operating on drum segments. One switch [LS(*a*)] is open in position No. 1 but closed in all other positions; the other [LS(*b*)] is open in the highest-number position but closed in all other positions. The question of alternative positions in the control circuit for the limit switches will be dealt with in a later section.

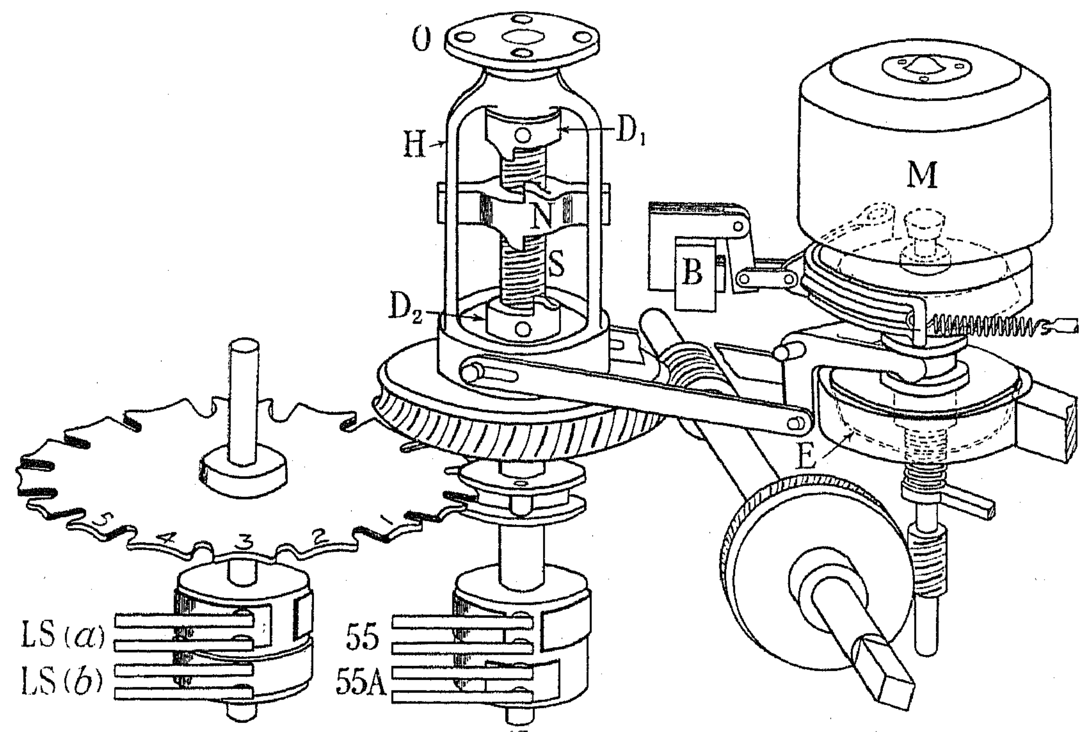



**Fig. 19.**—Essential parts of motor drive mechanism.

M. Motor.
B. Brake magnet.
55, 55A. Auxiliary contacts.
LS(*a*), LS(*b*) Limit switches.
O. Main low-speed shaft.
N. Sliding nut.
S. Screw thread on shaft.
$D_1$, $D_2$ Rotating dogs.
H. Slotted housing.
E. Braking surface.

The provision of a direct mechanical stop on the final low-speed shaft, when a motor is run at speed through reduction gearing, involves massive parts to avoid fracture as, if the motor is stalled by running up against the stop, the mechanism will be subjected to great strain. The device indicated on the main shaft O provides a mechanical stop and also a definite safeguard against overrunning if a limit switch fails or a contactor " sticks in," and involves no shock or strain to any part. Before the details of this device are considered, attention should be given to the problem of a tap-changer of the type which uses duplicate selector switches and transfer switches. The timing diagram (Fig. 20) shows that one revolution of the main shaft completes six switching operations. It is necessary so to design the mechanism that the opening of the first transfer switch does not commence until the shaft has moved several degrees, and the closing of the second transfer switch must be completed by a similar amount before the revolution has been completed. The six switching movements occupy the angular spacing between these limits. If a tap-changer has, say, 10 steps, the mechanism must be capable of moving only 10 complete revolutions, and its movement must be arrested before it has overrun by the amount of the angle *a* or *b*. In the device indicated

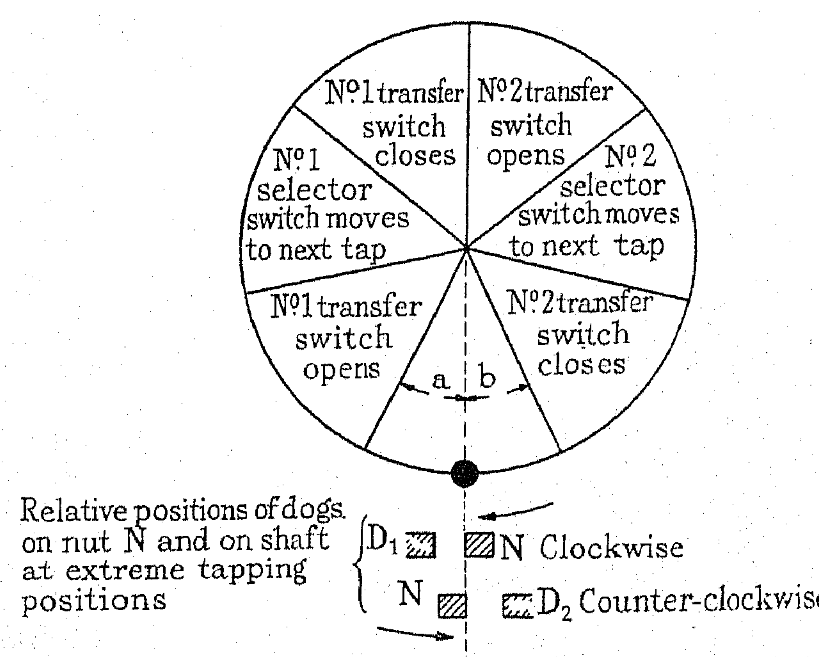



**Fig. 20.**—Switching sequence of tap-changer with duplicate selector switches and transfer switches. Conditions shown are for clockwise direction. Movements of transfer switches are reversed for counter-clockwise rotation.

in Fig. 19 (British Patent No. 374170) a coarse-pitch screw S engages with a nut N which has a dog projection at either side. This nut moves up and down as the shaft revolves, and is prevented from rotating by slots in a bell-shaped housing H. Two dogs $D_1$ and $D_2$ revolve

with the main shaft O. They are so dimensioned and spaced, and the screw pitch is so designed, that the dogs on the nut N and either $D_1$ or $D_2$ do not come in contact over the normal range, and in positions Nos. 1 or 11 they fail to make contact by a few degrees only (see Fig. 20). The motor is coupled to the first worm through a spring-loaded friction clutch, the moving member of which is linked by levers to the housing H.

If an attempt is made to overrun the gear—either by motor or by hand—at either end of the tapping range, the dogs on the nut N and either $D_1$ or $D_2$ come into contact, and housing H is turned and immediately declutches the motor. The moving member of the clutch is carried over to a braking surface E, which arrests the movement of the mechanism without shock. With this device, limit switches may be short-circuited while the motor is running, without any possible damage resulting to the mechanism.

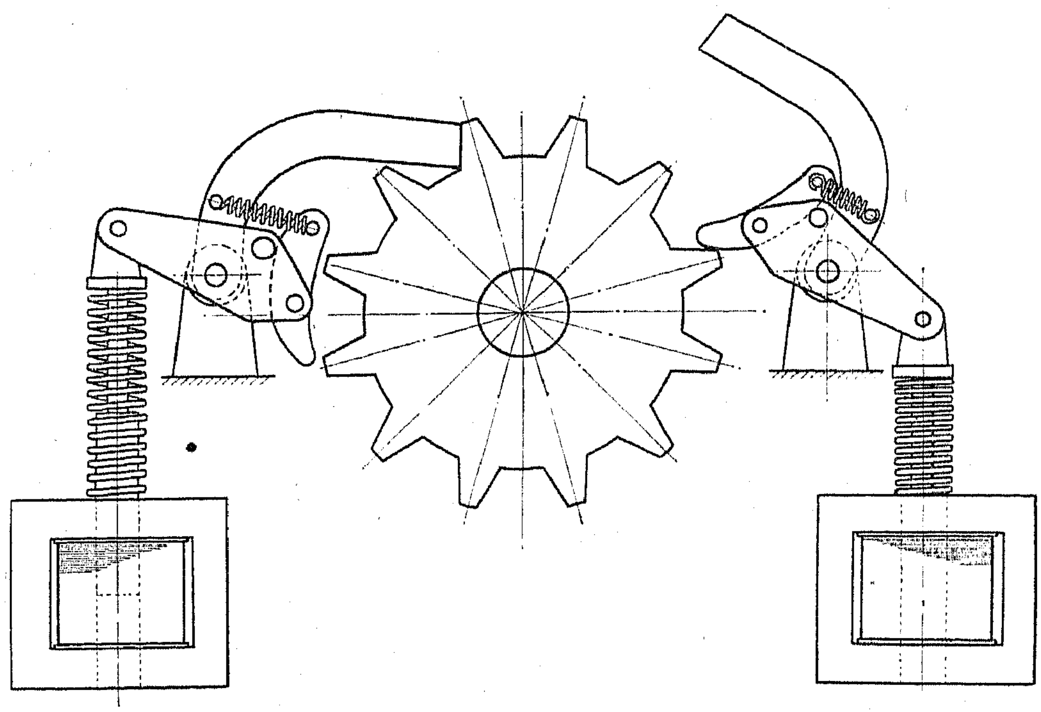


**Fig. 21.**—Ratchet and solenoid operating mechanism.

A spring-loaded brake shoe on the motor pulley is controlled by a magnet B whose coil is connected in parallel with the motor, so that the brake is released when the motor is energized and is re-applied by spring pressure to bring the motor rapidly to rest as soon as contact 55 opens.

For operation by hand, a square end is formed on the intermediate worm shaft and a dog clutch (not shown) is operated when the handle is engaged, so that the motor is automatically uncoupled whilst the handle is in position. In some designs electrical contacts in the control circuit are broken when the hand drive is engaged, but, in the author's opinion, automatic mechanical decoupling of the motor is to be preferred.

**(ii) Protection of motors.**

Small motors cannot be adequately protected against overloads by fuses as these have to be rated sufficiently high to withstand the frequent starting current-rushes and only provide protection against major faults, e.g. short-circuits between terminals, earth faults, etc. As the movement of a tap-changer is in definite steps, prolonged overloading of a 3-phase induction motor by running on single-phase does not arise, but the danger lies in attempting to restart the motor by energizing only two phases after a fuse has blown in one line. The most satisfactory form of protection against this condition and against normal overloading is the thermal overload relay whose heaters carry the currents of at least two phases of a 3-phase motor. The contacts of the relay are connected in series with the contactor coils. The opening of the relay contacts prevents further energizing of the motor windings, until the relay has been reset by hand.

**(iii) Solenoid-operated mechanisms.**

Tap-changers which require a series of switching operations on both selector switches and transfer switches in order to change taps are usually motor-driven, but where the switching movement is simply that of a few degrees' movement on a selector switch or cam for the operation of a contactor, operation is sometimes by solenoid and ratchet mechanism. An example of this is shown in Fig. 21.

The tapping selector-switch spindle is connected directly to the ratchet wheel, and the angle between two teeth corresponds to the movement for one tap-change. The ratchet wheel is moved in either direction by the two spring-loaded solenoids—one being used for forward movement and the other for reverse. The solenoid plungers are normally held up by the compression springs, and the linkages occupy the positions shown on the left-hand side. When the solenoid is energized the plunger is drawn and the larger locking lever is raised. The smaller lever takes up a position relative to the toothed wheel such as that shown in the right-hand view and, when the solenoid is de-energized, the compression spring turns the wheel by one tooth pitch, and the locking lever resumes its initial position. This type is usually only applied to small tap-changers where the forces required are small, as otherwise large operating currents would be required by the solenoids.

### (e) Summary of Desirable Features of Design

Although economic conditions and available space sometimes prevent their complete adoption on smaller equipments, the following features are, in the author's opinion, to be desired:—

(i) The tap-changer should preferably be built as a complete unit which is bolted to the transformer tank, so that all parts are readily accessible without disturbing the transformer.

(ii) The tap-changer should be so placed and dimensioned that rail transport is possible with the tap-changer in position, thus avoiding erection work on site.

(iii) Ease of maintenance. There should be easy access to all essential parts. Where there are separate arcing contacts these should be in a separate tank which can preferably be lowered for inspection without draining oil or breaking oiltight joints. Selector switches, which do not break current, require only infrequent inspection, but this is facilitated if an oiltight barrier is fitted between the selector-switch tank and the transformer tank (see Fig. 15), although this is sometimes difficult to accommodate when there are a large number of tappings and high-voltage tests have to be met. The motor driving gear should preferably be accessible from ground level, and all auxiliary contacts, etc., should be in accessible positions. Reduction gears should be totally enclosed and oil-immersed.

(iv) Prevention of faulty operation. Although there is slight risk of the gear stopping between steps, schemes are to be preferred which do not overload the windings during a tap-change. Preventive reactors should be continuously rated unless completion of tap movement is ensured by stored energy. A mechanical safeguard should be provided to prevent overrunning due to wrong connections of the limit switches or their failing to function. Mechanical, in preference to electrical, means of decoupling the motor should be provided to protect an operator when cranking by hand.

(v) Motors. Except for the smallest sizes, 3-phase motors are to be preferred, but satisfactory single-phase and d.c. motors, suitable for direct starting, are available.

## (5) CONSIDERATIONS OF INSULATION DESIGN WITH REFERENCE TO NORMAL (50-CYCLE) INSULATION TESTS AND "IMPULSE" VOLTAGES

The tap-changing gear is subjected to voltage tests in a similar manner to the transformer windings to which it is connected and, on fully insulated transformers, is usually subjected to a 50-cycle voltage test to earth of approximately twice the line voltage for 1 minute. The voltage test between phases of a 3-phase switch is dependent on the location of the tappings on the winding limb, and is usually applied in the induced-voltage test when the windings of the transformer are excited at approximately double voltage for 1 minute with the frequency increased to reduce the magnetizing current.

For star-connected windings which have been designed for operation with the neutral point solidly earthed, the induced-voltage test only is applied, but the applied voltage is increased to 2·8 (or sometimes 3·46) times normal. In addition to these tests, type tests are frequently specified which involve testing at 50 cycles per sec. between adjacent tapping contacts on a sample switch at voltages ranging from half to two-thirds line voltage for periods varying from 1 minute to 3 seconds.

Considerations of co-ordination of transformer and line insulation and impulse-voltage testing are likely in the future to impose more onerous conditions of insulation strength on the tap-changing gear, and the conditions are linked up with the electrostatic design of the transformer windings. A recent paper* recommended impulse test voltages for a series of (working) line voltages. These are not at present part of any accepted British Standard Specification, but it is reasonable to assume that values not differing by much from those recommended will in due course be standardized.

For 132-kV working voltage, the recommended gap setting corresponds approximately to a 650-kV impulse with 1/50 positive wave, i.e. to a value approximately equal to 6 times the peak phase voltage, $\left(\frac{6 \times 132}{\sqrt{3}} \times \sqrt{2}\right)$kV. It is known that under impulse conditions, without the use of special static shields, etc., the initial voltage distribution over the winding does not follow a straight-line law, owing to the end coils having to carry the capacitance currents of the following coils. (This subject was dealt with in a paper recently presented to the Institution.†) If the transformer tapping range is 20 per cent, under ideal conditions, i.e. straight-line distribution, the voltage across the tapping selector switch in the above case might be 1·2 times the normal peak phase voltage and, under actual conditions of normally-designed core-type transformers, might be 2 to 3 times as much. Similarly, the voltages to earth are much increased under impulse conditions. In the case of a star-connected transformer with solidly-earthed neutral point the voltage to earth of the tapping section may be 75 per cent of the applied impulse if the tappings are arranged in the middle of the coil stack, and may be rather greater than 100 per cent of the applied impulse if the tapping coils are arranged about 25 per cent away from the line-end coils. On delta-connected windings or star-connected windings with isolated star point, no matter what position in the coil stack the tappings occupy, the voltage to earth may rise to nearly twice the applied impulse voltage.

It is clear, therefore, that tap-changing gear which has been designed only to pass the British Standard 50-cycle tests by a small margin may be unsuitable when co-ordination of line and transformer insulation on a basis of impulse test voltages is accepted practice.

## (6) METHODS OF ELECTRICAL CONTROL

Electrically-operated tap-changers can be arranged for either remote electrical or automatic control. Two essential parts of all control circuits are (*a*) the mechanically operated contact (contact 55 in Fig. 19), and (*b*) the limit switches. The latter prevent overrunning of the gear and the former ensures that, when started, the

* T. E. Allibone and F. R. Perry: "Standardization of Impulse-Voltage Testing," *Journal I.E.E.*, 1936, vol. 78, p. 471.
† See Bibliography, (32).

apparatus continues to run for at least the distance of one tap-change (provided the auxiliary supply persists).

There are differences of opinion as to the positions the limit switches should occupy in the control circuit. Some engineers advocate their inclusion directly in the motor circuit on the grounds that, if included in the contactor-coil circuit, they may be rendered inoperative if a contactor "sticks in." This is correct but involves very critical angular timing between the movements of the limit switches and of switch 55 (Fig. 19), which are on different shafts, and the timing may be upset by any backlash which may develop. In addition, damage may result if the connections of the two limit switches are reversed. In the author's opinion, the contactor-coil circuit is the preferable position as it gives much wider tolerances on the angular timing, and protection against a contactor sticking-in is provided more safely by a positive mechanical device similar to that indicated in Fig. 19.

### (a) Remote Electrical Control

A circuit for the remote electrical control of one tap-changer is indicated in Fig. 22(*a*). A 3-phase supply is used for the control circuit, and the direction of rotation of the 3-phase induction motor (67) is determined by the closing of one of the two mechanically interlocked contactors 65 and 66. Two of the poles only of each contactor complete the circuit for the motor, the third pole being connected to the mechanically operated contact 55, which is open in each completed tap position and is closed when a tap-change is in progress. Contact 55 and the third pole of 65 or 66 (depending on the direction of rotation) provide a hold-in circuit which ensures that the tap-changer movement is completed. The closing of either contact R or contact L energizes the coil of contactor 65 or contactor 66. The motor starts up and, if contact R or contact L is broken shortly after being made, the gear will run for one step and then stop. If contact R or contact L is held closed for a period corresponding to more than one tap-change, the motor will continue to run for a number of completed operations, but, if desired, the circuit can be modified to give operation by one step only each time contact R or contact L is closed.

The brake coil 67B is energized in parallel with the motor, and the braking force is applied when the supply to the motor ceases. In series with two of the motor leads are connected the heaters of the thermal overload relay 29, whose contacts are connected in the contactor-coil circuits, so that the latter cannot be energized if the motor shows signs of distress.

The limit switches are connected in the contactor-coil circuit rather than in the motor circuit for the reasons given earlier in this section, and serve to prevent either contactor 65 or contactor 66 being energized to run the gear beyond the normal limits of travel.

With the above circuit, it is necessary to hold the control switch while the tap-changer makes a movement of several tapping positions. It is sometimes necessary to have a preselector form of control by which the operator can select the tap he desires to move to, and can leave the control switch with the knowledge that the gear will move to the required tap and then stop.

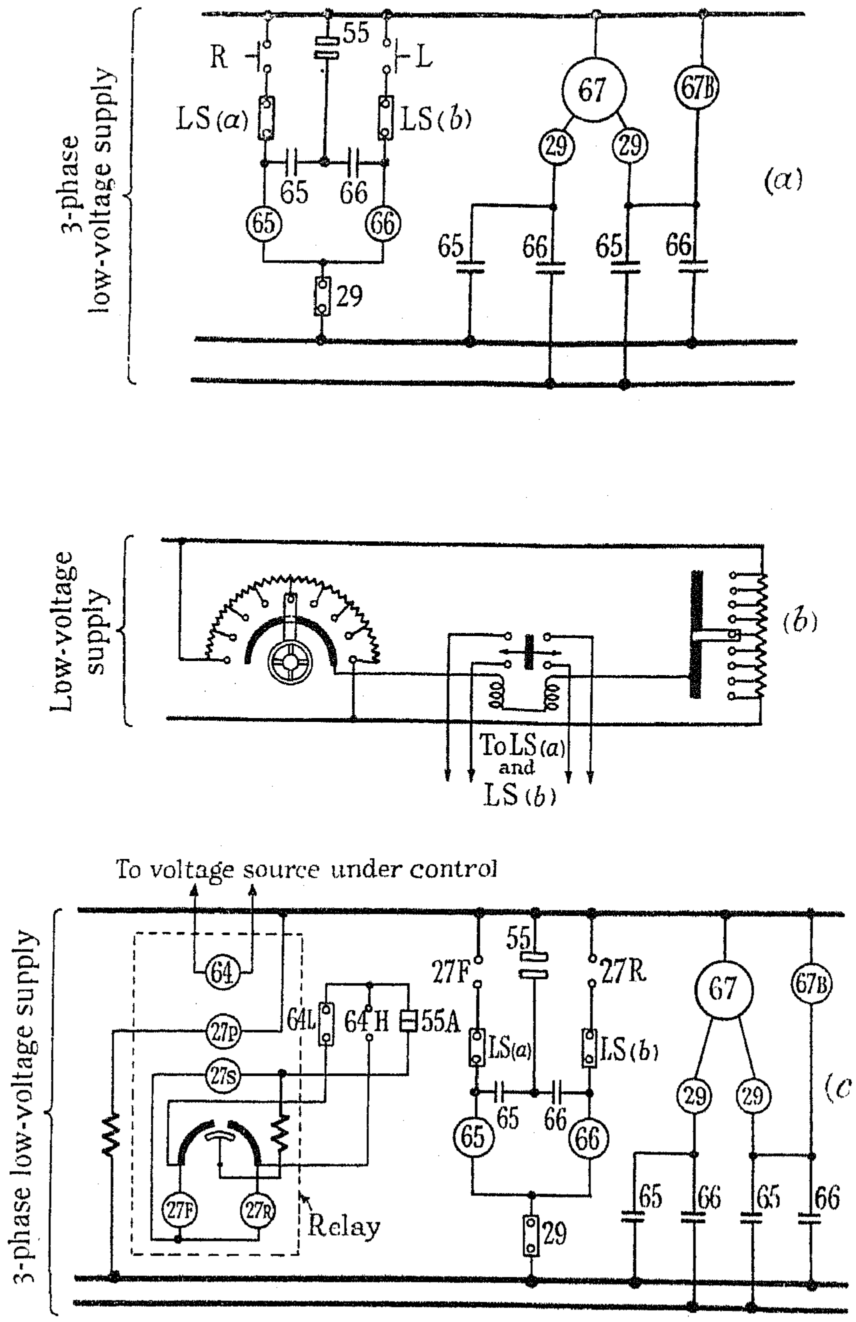
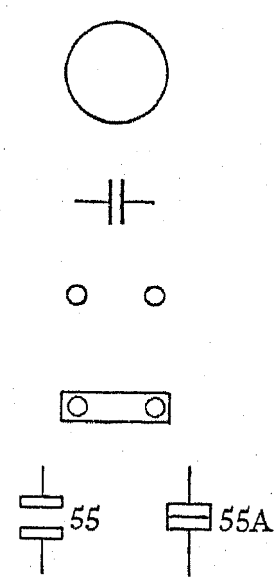



Fig. 22.—Remote electrical and automatic control of tap-changer.

*Key to Fig. 22.*




Motor winding, coil of contactor or relay.

Normally-open contacts, close when contactor coil energized.

Normally-open contacts, close when relay coil energized.

Normally-closed contacts, open when relay coil energized.

Mechanically-operated contacts on tap-changer mechanism.

| | |
|---|---|
| R.L. | "Raise" and "lower" contacts of control switch. |
| L.S.(*a*) L.S.(*b*) | Limit switches. |
| 27 | Time-delay relay. |
| 29 | Thermal overload relay. |
| 64 | Voltage-regulating relay. |
| 64H, 64L | "High" and "low" contacts of voltage-regulating relay. |
| 65, 66 | Mechanically-interlocked 3-pole contactors. |
| 67 | 3-phase motor. |
| 67B | Brake coil. |

One form of control which achieves this result is shown in Fig. 22(*b*). Two potentiometer resistances are connected across the supply: the left-hand one is connected to a rotary switch at the control point and the right-hand one is similarly connected to a rotary switch on the tap-changer mechanism. A directional relay is connected between the common connections of the switches, and the pairs of contacts on the relay occupy the positions of contacts R and L in the circuit of Fig. 22(*a*).

With the gear at rest in a completed tap position, the contacts of both switches occupy the same relative positions and no current flows through the relay, but, if the handwheel of the control switch is turned in either direction, current will flow through the directional relay, which will then close one of its pairs of contacts to run the tap-changer for any desired number of complete tap positions until balance is restored in the relay.

With this method, any number of tap-changers can be controlled simultaneously by mounting more than one switch and potentiometer on the one handwheel.

### (b) Automatic Control to Maintain Constant Voltage

The essential difference between circuits for automatic control and for remote control consists in the inclusion of a voltage-regulating relay and time-delay relay in place of the control switch, as indicated in Fig. 22(*c*). The contacts 27F or 27R of the time-delay relay occupy the positions of contacts R or L of the circuit of Fig. 22(*a*). Types of voltage-regulating relay which work on different principles are described later. In the diagram of Fig. 22(*c*) the relay coil 64 is connected across the voltage which is to be controlled and makes either contact 64L or contact 64H when the voltage is lower or higher than normal. To prevent the tap-changer responding to momentary voltage fluctuations, the closing of contacts 64H and 64L operates only on the circuit of a two-way time-delay relay 27, and a tap-change is only initiated by the eventual closing of the contacts 27F or 27R of the time-delay relay (after the voltage-regulating-relay contacts have remained closed for a definite period: this period is usually adjustable). In order to reset the time-delay relay, i.e. to open its contacts in readiness for the next step movement, the circuit is completed through a second mechanically-operated contact 55A on the tap-changer mechanism which is closed when the gear is at rest in each completed tap position but opens during the period when a tap-change is in progress. When the voltage is high or low, the relays will control the tap-changer in the appropriate direction until the voltage is restored to normal and the voltage-regulating relay balances again.

With the arrangement shown in Fig. 22(*c*), if the supply to the relay coil 64 fails, contact 64L will be made and the tap-changer will be run automatically to the position of maximum voltage. To avoid this, "no-volt" contacts (not shown) are usually included in the circuit and are so connected that, when the voltage supply to the relay coil fails, the tap-changer either remains stationary or runs automatically to the position of minimum voltage. If the auxiliary supply were to fail during a tap-change the gear would remain at rest after the supply had been restored until contact 55A had been short-circuited temporarily or reclosed by turning the gear by hand. To avoid this, additions (not shown) can be made to the circuit so that the apparatus will respond immediately to restoration of the supply.

With the addition of a line-drop compensator (not shown), operated from current transformers, the effective "voltage balance point" of the relay can be arranged to increase automatically as the load increases, thus producing a compounding effect.

### (c) Relays for Automatic Control

An early form of voltage-regulating relay consisted of a beam, pivoted in the centre, with a tension spring at one side and an iron-cored solenoid at the other. The pull of the spring and of gravity on the solenoid plunger plus the magnetic pull were so arranged that the beam remained horizontal at 100 per cent voltage but sloped in either direction as the voltage increased or decreased, and so made contact with either of two fixed contacts. With this design the available forces are small and operation may be affected by pivot friction. Hold-on coils are also usually necessary to avoid chattering of the contacts.

This type has been improved recently by one manufacturer by the elimination of springs and hold-on coils; and a considerable increase has been made in the forces available, by special design of the magnetic circuit, so that a two-way tilting mercury switch can be used for the contacts. The pull is made practically constant for a given voltage independently of the position of the core, so that operation is stable. This relay has been described fully elsewhere.*

Another type of relay (Fig. 23) avoids the difficulty of pivots by suspending the solenoid core on two leaf springs which permit vertical but not lateral movement. The weight of the core is partly balanced by the pull of a spring which is capable of adjustment. At the lower end of the core a flexibly mounted contact connects with the higher or lower fixed contacts (64H or 64L) on high or low voltage. Oscillations set up by momentary changes in the supply voltage are damped out by a vane working between the poles of a permanent magnet. The core has three stable operating positions (floating, high, and low) by virtue of the soft-iron disc at the top of the core, which works between the poles of three sets of permanent magnets. "Under voltage" protection is provided by the lower contacts 64UV. Sometimes a separate time-delay relay is used for each direction, but the relay in Fig. 23 includes at the bottom an induction-type time-delay relay which serves for both directions. The disc of the relay moves in either direction depending on whether contact 64H or contact 64L remains closed, and the movable contact arm is driven from the relay spindle by gearing. The upper magnet carries an exciting winding 27P and a secondary winding 27S which is put in series with either the forward winding 27F or the reverse winding 27R on the lower magnet, depending on whether 64H or 64L is closed. Immediately after the disc has begun to rotate, contact is made on the drum contact to one side and the other, thus

* See Bibliography, (31).

putting the remaining coil on the lower magnet in parallel with the coil already energized. In due course the contact arm makes circuit with the fixed contact 27F or 27R. The time setting is adjusted by varying the positions of the fixed contacts 27F and 27R. The relay is reset by the opening of contact 55A during a tap-change, but it is of the "slow reset" type. This allows the time-delay to be set to correspond closely to

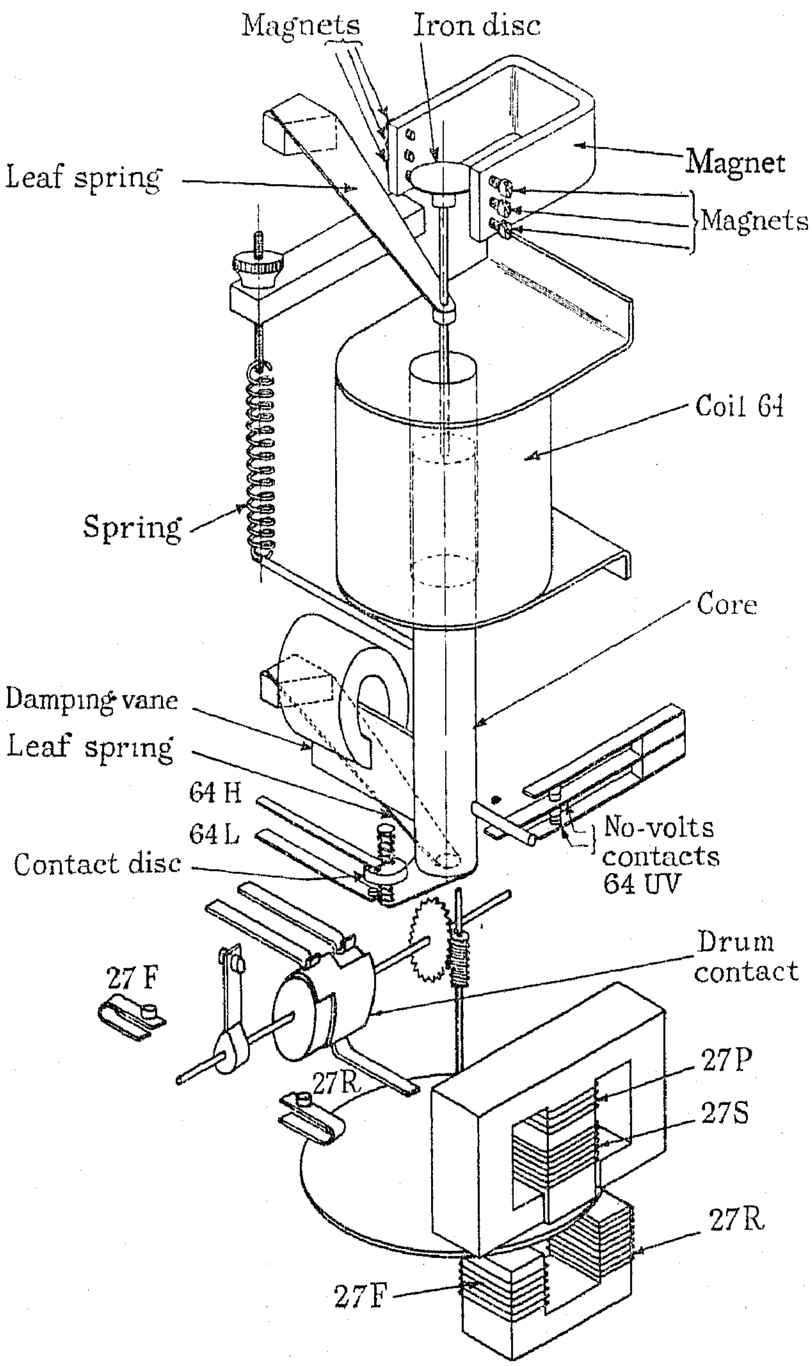



Fig. 23.—Combined voltage-regulating relay and time-delay relay.

the average voltage conditions. With instantaneously-resetting relays the time-delay period, if interrupted by the momentary opening of contacts 64H or 64L, must recommence from zero. In general, the resetting time of the relay of Fig. 23 is about one-third of the time-delay setting.

An alternative form of voltage-regulating relay works on a different principle and uses resonance in a circuit consisting of an iron-cored reactor, a resistor, and a condenser, in series (British Patent No. 414647).* When an alternating-current supply is fed to such a combination, it is known that, when working near the saturation point of the reactor, there is a critical voltage above which a large increase in the current takes place suddenly as the voltage is increased. In the voltage-regulating relay two such circuits are connected in parallel [see Fig. 24(*a*)] and are tuned to have slightly different characteristics, i.e. their critical voltages are slightly separated. A magnetically operated contactor is connected in parallel with each condenser and, as the voltage becomes high or low, the voltage across the condenser changes suddenly and so operates the high or the low contact. The contact L remains closed while the voltage is low and until the critical voltage is reached. The other one closes at the critical voltage of the second circuit when the voltage becomes high.

A third method employs a saturated reactor in parallel with a condenser [Fig. 24(*b*)]. As the voltage is increased the leading current through the condenser

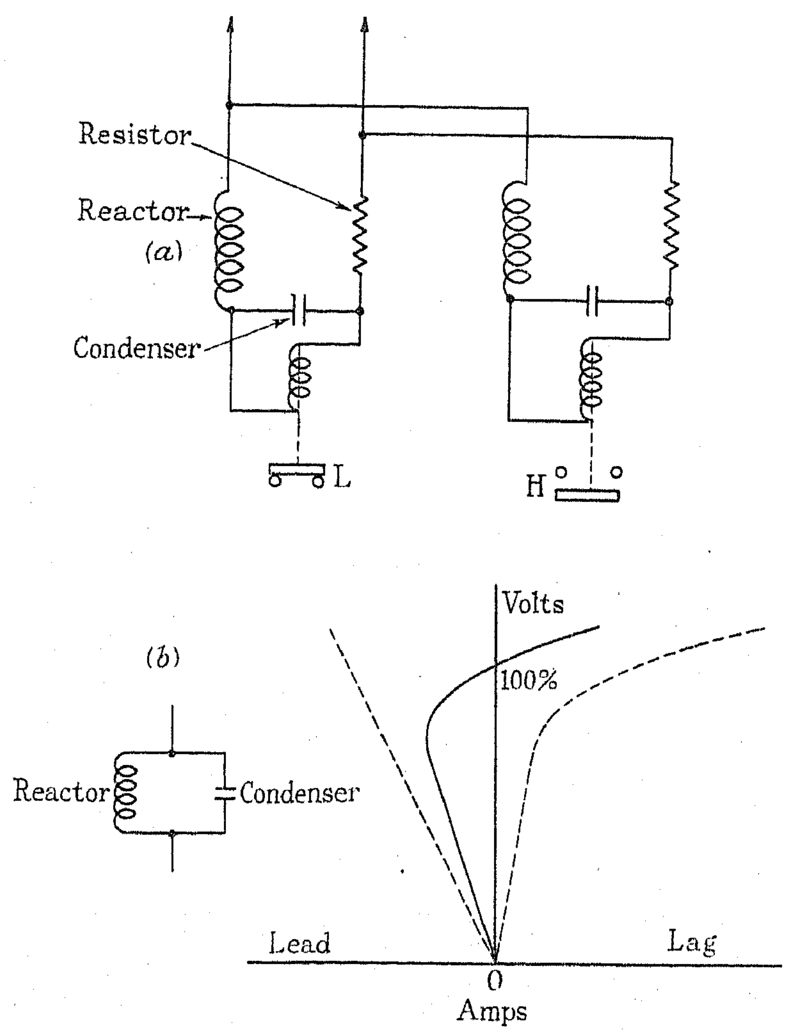



Fig. 24.—Voltage-regulating relays using saturated reactors and condensers.

increases at a uniform rate, whereas the lagging current of the reactor departs from a straight-line law owing to saturation. The combined current of the two circuits in parallel follows the full-line curve of Fig. 24(*b*), and it will be seen that the current is in phase with the voltage at 100 per cent voltage but becomes leading or lagging as the voltage of the circuit drops below or rises above normal 100 per cent value. The reactor and condenser are put in series with one of the coils of an induction-type relay which is arranged to exert no torque on its disc when the current and voltage are in phase, but turns the disc in one direction or the other when the current leads or lags behind the voltage.

* See Bibliography, (29).

### (d) Electrical Position Indicators

Three principal types of electrical position indicator are in common use: (i) lamps, (ii) phase-shifter type, (iii) potentiometer type. Any indicating device should not be affected by appreciable changes in the supply voltage. Types (i) and (ii) meet this condition, but not all the designs of type (iii).

The lamp type requires a large number of pilot cables. The phase-shifter type usually requires only two extra cores, and consists virtually of two 3-phase induction motors whose primary windings are connected in parallel and likewise their single-phase secondary windings. The rotor of one is connected to the tap-changer shaft and any angular movement is reproduced in the second, which serves as an indicator.

The potentiometer type requires only one core and is made in two classes. The first class uses a tapped resistance or transformer (as transmitter) at the tap-changer. This is supplied in parallel with coils on the indicating instrument. A rotary selector switch on the transmitter varies the voltage which is supplied to other coils on the "receiver" and, by special design, the instrument can be made independent of wide variations in supply voltage.* An alternative type, which has been described elsewhere,† uses, as the transmitter, an inductive potentiometer consisting of two coils in series through which an iron core is moved and so varies the distribution of voltage between the coils. This device is employed to vary the voltage distribution between two fixed coils on the receiving instrument, and hence the flux distribution in their common magnetic circuit. A moving coil, consisting of a single short-circuited loop passing over the common core of the two coils, takes up positions corresponding to the movement of the core at the transmitter. This design is not affected by variations in the supply voltage.

## (7) ECONOMICAL REGULATING DEVICES FOR RURAL LINES

In low-voltage distribution in rural areas, owing to the much greater distance between houses, etc., appreciable voltage-drop is inevitable and, as a means of counteracting this, several forms of simple two-step booster equipments have been devised. Provided that the voltage variation is primarily due to drop resulting from the load current, i.e. there is no appreciable primary voltage variation, the control may be operated automatically according to the value of the current instead of by means of a voltage-regulating relay: this cheapens and simplifies the control gear. One type of current-controlled booster is shown in Fig. 25. This is typical of a number of types of one-step and two-step boosters for use on tail-end distributors which have been developed in this country, on the Continent, and in the U.S.A.

A series booster transformer is connected in the line and one end of its primary winding is connected to the centre tapping of a reactor, which is controlled by two switches X and Y, whose operating coils are fed from the secondary of a current transformer in the line. Switch X is so arranged that it remains closed until the load current exceeds about 75 per cent of the full-load value. Switch Y remains open until 35–40 per cent full-load current is reached, and is closed for all higher values of current. This gives three switching positions, which are shown in Fig. 25 [(*b*), (*c*), and (*d*)]. In the first, switch X only is closed, the booster is short-circuited through half the reactor winding, and there is no boost. At 35–75 per cent full load, switch Y closes and the reactor acts as a potential divider impressing half voltage on the primary of the booster, which injects one step of boost into the circuit. When the load exceeds 75 per cent, switch X opens, thus connecting the booster primary across the line in series with half the reactor winding and giving approximately double the amount of boost. The values of the steps are usually of the order of 3 to 4 per cent. With decreasing currents the cycle is reversed.

In some cases the switches are operated by solenoids. These are difficult to design to have approximately

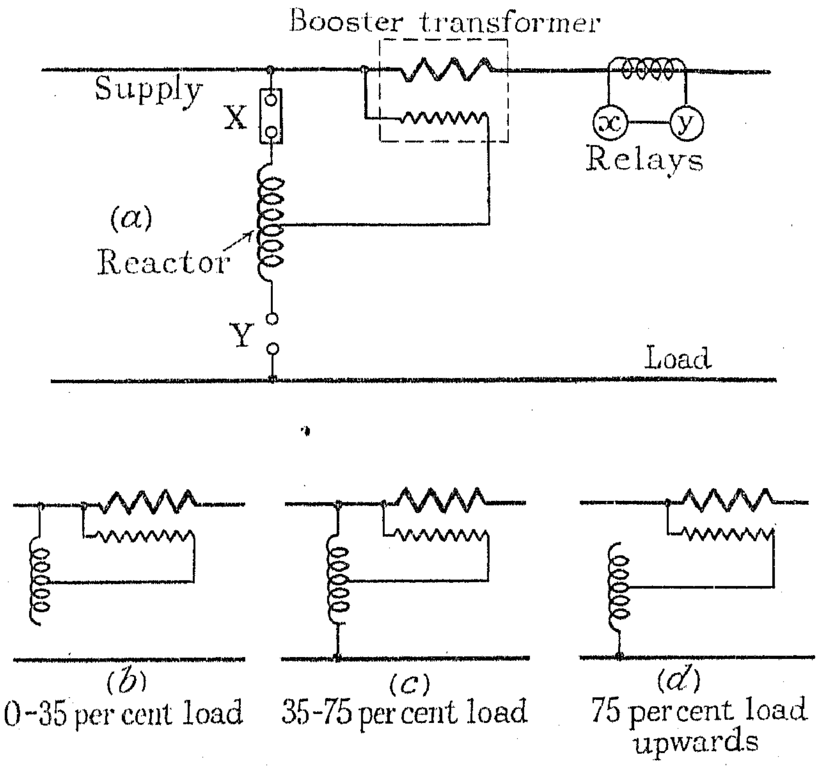



**Fig. 25.**—Current-operated two-step booster.

equal pull-in and fall-out values, and bimetal-strip-type relays have been used as an alternative. Alternative types with one or two steps of boost have been designed to operate by a form of voltage relay on the principle of Fig. 24(*a*).

## (8) OPERATING EXPERIENCES AND TROUBLES

Any form of mechanism, particularly if it is to be automatically controlled, must be subjected to an extensive life test to discover any weaknesses in design or construction. After any defects revealed in this way have been remedied, the test is usually continued for a number of operations corresponding to several years' normal service as a type test, before a tap-changer of a particular design is supplied to a customer. Despite this testing, defects sometimes appear during service on the first few equipments, and detailed changes may become necessary.

The following observations are the result of several years' experience. In some early designs, porcelain

* See Bibliography, (33). † *Ibid.*, (35).

bushings were used for the transfer switches. Despite long life tests, several bushings developed cracks in service which proved to be due to heavy localized pressure resulting from irregularities at the ends of the porcelains. This difficulty was overcome by grinding the ends of the bushings of a switch in pairs, after cementing in position. In the author's opinion porcelain is not very suitable for switches which have to be operated frequently, and in later designs condenser-type wound-paper bushings have been used with complete success.

The contact backing springs of transfer switches have had to be more liberally designed than similar parts used in standard oil circuit-breakers, in order to avoid failures due to fatigue.

Pawls and latches of stored-energy mechanisms have had to be made of a specially tough nickel steel and case-hardened, but a preferable solution is to design so that the parts are not subjected to appreciable shock, and later designs have been made with this in view.

All auxiliary switch contacts in the control circuit should preferably be of the "rubbing" type, backed by ample spring pressure, so as to be self-cleaning.

Difficulties have arisen on automatic control due to the motor speeds and gear ratios not having been so chosen that the auxiliary contacts (see 55A in Fig. 22, and Fig. 19), which open during a tap-change to enable the time-delay relay to reset, remain open for a sufficiently long time. Automatically-controlled tap-changers in many cases operate more frequently than is necessary owing to low settings of the time-delay relay. An increase of setting from 30 to 60 sec. will probably reduce the number of changes to at least one-quarter without any greater variation in recorded voltage. The sensitivity of the voltage-regulating relay has to be adjusted to suit the size of tapping in each case, or hunting may result.

Before the introduction of thermal overload relays, cases arose of damage to operating motors due to wrong connections of limit switches and stalling of the apparatus in one of the end positions. The mechanical declutching device (Fig. 19) has removed this possibility. It has also solved the difficulties of providing a mechanical stop and of arresting the movement without strain in the drive and gearing.

The lubricating oil for the gearboxes should not freeze under winter conditions out of doors, as the apparatus does not operate for long enough periods to warm up the oil. Where bearings for auxiliary shafts in motor mechanisms are not oil-immersed, they are sometimes neglected although provided with greasers. Oil-less bearings of graphitic bronze provide a solution of this problem for lightly-loaded bearings.

The results of two cases of wrong connections were puzzling until investigated. A big voltage fluctuation during a tap-change was reported. The connections should have been as indicated in Fig. 10, with both selector switches on the same tap in all the operating positions. Actually two of the reactor leads were found to be reversed (see Fig. 26), so that, when the reactor was in the bridging position, instead of dividing the voltage between two taps it injected a voltage equal to double the amount. This trouble can be avoided by measuring the voltage ratios in the bridging positions whether used as running positions or not.

Another case proves that reliance cannot be placed on ratio tests made with a 3-phase supply to delta-connected primary windings. A tap-changer was applied to the primary winding of a delta/star transformer and was automatically controlled by a relay connected across the secondary. The transformer and tap-changer had been tested in the factory, but work was done inside the transformer tank on site which resulted in the accidental fracture of one of the tapping connections to the switch on one phase. With 3-phase supply to the primary side, the secondary voltages of the three phases were checked on open circuit in all switch positions, and the transformer was put on load after the automatic gear had also been checked. After a movement of the switch the voltage on one phase dropped very low owing to the effect of the open-circuited tap. This did not show up during the test on open circuit, as, with a 3-leg core and a 3-phase supply to a delta-connected winding, the flux distribution is not affected by an open circuit in one phase and symmetrical 3-phase voltages are induced in the secondary winding. The remedy for this trouble is to make all ratio tests with single-phase supply to each of the three phases in turn.

Care has to be taken in regard to the connections of the secondary windings if the relay is supplied from a 3-phase voltage transformer. This is sometimes outside the contract of the transformer and tap-changer manufacturer, and three secondary fuses have sometimes been supplied. If the relay is connected across one pair of phases and other instruments across a second pair, the blowing of the fuse in the common phase puts the relay and other apparatus in series across the third pair of phases. This produces the effect of an abnormally low voltage across the relay, and the tap-changer will therefore be run to the position of maximum voltage. The remedy for this is to remove the fuse from the common phase and to earth this point.

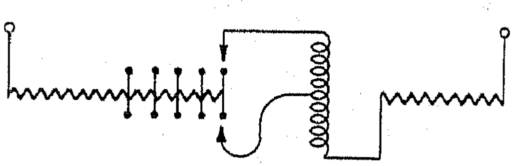


**Fig. 26.**—Wrong connections of mid-point reactor.

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## DISCUSSION BEFORE THE INSTITUTION, 25TH FEBRUARY, 1937

**Mr. Johnstone Wright:** The author mentions that the Central Electricity Board in 1928 decided to specify on-load tap-changing for all transformers of 132 kV; the Board actually went further than this and specified on-load tap-changing for all transformers of 2 000 volts and over. At that time very little experience was available of on-load tap-changing gear, and there were many (including some transformer designers) who thought that the Board's engineers were very venturesome in specifying this form of equipment.

The first tenders the Board received for transformers with on-load tap-changing gear put forward the following alternatives: (1) On-load tap-changing gear incorporated in the high-voltage winding (cost represented by 100). (2) Single-unit booster regulator in the high-voltage neutral in parallel with the windings of the main transformer (113). (3) Single-unit booster regulator in the high-voltage neutral, with auto-transformer controller (113). (4) Two-unit booster regulator on low-voltage side of transformer (125). There was obviously a great financial advantage in having the tap-changing incorporated in the high-voltage winding of the transformer, and this fact, coupled with the higher efficiency and smaller floor-space, induced the Board to choose that type of apparatus. We have now 301 132-kV transformers and 373 lower-voltage transformers with this form of equipment, and their performance has amply justified the decision to utilize the most economical and compact form of voltage control available. The Board have spent something like £4 000 000 on transformers, and the adoption of this type of tap-changing gear in the high-voltage winding has meant a saving of about £500 000.

Experience with the tap-changing gear has not been uniformly good, but there have been no serious troubles. In some of the early designs minor modifications have had to be made. On the mechanical side the trouble was mainly in connection with the overrunning of the gear, and it became essential to fit locking devices to prevent this. There were also some small troubles with the driving gear. On the electrical side the trouble was mainly due to the tendency of the diverter switches in connection with the reactor-controlled gear to flash-over; tracking over bushings and short-circuiting between segments of controllers occurred where these were used directly for tap-changing. It is noteworthy that where the transformer designer has kept his tap-changing gear clear of the main transformer tank we have had no major case of trouble in the main windings of the transformer.

Maintenance of the gear has not given the Board's engineers much concern. The amount of maintenance necessary seems to vary with the type of reactor used. The reactors with closed magnetic circuit seem to be at a tremendous disadvantage as compared with the air-gap type, and I should be glad to have the author's comments on this.

**Mr. A. G. Ellis:** The evolution of on-load tap-changing equipment to its present state has been very rapid, owing, so far as this country is concerned, largely to the development of the grid. I remember a very early case some 30 years ago, on the Continent, of tap-changing gear required for a large furnace transformer. The best idea which was conceived at that time was to put a separate oil switch on each tapping, all the switches being driven by a long shaft with a series of individual cams; the result was a design in which the tap-changer was many times as big as the transformer itself. When one compares such an arrangement with the very compact designs shown in the paper, the contrast is very marked.

In Section (4)(*e*) the author endeavours to summarize the desirable features of the design. I should like to call attention to Nos. (i) and (ii) of these, and to say that we have been able to achieve designs of transformer tap-changers fulfilling both these requirements for the largest and the highest-voltage transformers. It is very desirable to have the whole of the gear self-contained, so that if anything goes wrong with any part of it the trouble does not spread to the transformer proper. It is now common practice for the tapping selector-switch chamber to be isolated from the main transformer tank by a barrier of insulating board fitted with oiltight tapping terminals. This is, I believe, now standard practice for the Central Electricity Board. This problem does not present undue difficulties, except in very high-voltage transformers, with large numbers of tappings, involving, for example, from 30 to 50 tappings on a 3-phase, 132-kV winding. If the neutral point is earthed the working voltage of the tappings above earth may be of the order of 30 000 volts and the test voltage of the order of 80 000 volts. If the neutral is insulated the test voltage (for a 132-kV winding) of the tappings and tapping terminals to earth is 265 000 volts, and the problem is much more difficult and possibly impracticable.

With the self-contained design of tap-changer, provided with barrier terminal board, it is quite possible to build a transformer so that the complete tap-changing gear can be fitted at a later date, if it is not desired to purchase and install it at the outset.

As regards large transformers, for this country the size is usually restricted by the railway loading gauge, and this has led to designs of very large transformers having the tap-changing gear fixed on to the end, for transport complete. Such designs involve many and long high-voltage leads from the windings to the tap-changer, but this problem has been satisfactorily solved by the use of paper-insulated flexible cable; very often this is achieved without any joints between the actual winding tappings and the tapping selector switches. In the Continental design shown in Fig. 16 the running of the tapping leads is somewhat simpler, the tap-changing gear being vertically above the transformer, but this design suffers from the disability that it is necessary to remove the tapping switches in order to transport the transformer by rail.

I should like to urge the restriction of the number of tappings required, and the voltage range of the tappings, as far as is practicable to suit the operating conditions. An unnecessarily large voltage range means a more costly transformer, certainly a more complicated one, and one which is possibly ultimately less reliable. The two questions of the range of voltage and the number of tappings are very much inter-related. In the case of a tap-changer operating with protective reactor, one cannot

cheapen the apparatus very much by reducing the number of steps, for example, to half, because the protective reactor has to be doubled in capacity as the kVA per step is doubled; one can achieve a more compact design only by reducing the total range. If one uses a protective resistor instead of a reactor this difficulty is not so severe, as the resistor is a relatively smaller item in the cost of the total equipment. The resistor, which is used with the smaller types and the use of which is extending upwards, has, however, certain limitations, one of these being that it is not possible to use the mid-point as a running tapping as one can with the reactor. By using the mid-point of the reactor as a running position the number of winding tappings can be halved and the tapping problem much simplified.

I should like to plead for more standardization by supply engineers. The C.E.B. standardized their conditions at the outset, and they have consistently adhered to those standards, and thus simplified the work of the manufacturer. Apart from them, however, the range of requirements is rather bewildering, and, in spite of the rather late stage in development, I hope that the British Standards Institution will endeavour to effect some degree of standardization in the operating reqirements.

**Mr. F. C. Winfield:** I imagine that, as the years pass, the development of electric supply arrangements in this country will tend to a division into a number of supply areas not normally connected and each comprising a triple system in the form of a primary system consisting of the 132-kV and 66-kV networks plus the generator plant, a secondary major distribution system representing the 33-kV or 11-kV networks, and a tertiary network formed by the local low-voltage distribution systems. The important point of difference from present-day arrangements will lie in the connection of the generating plant to the primary network. In the early days of electricity supply the generators were connected to the low-voltage distribution network. This method was soon found unwieldy and uneconomical, and the generators were therefore transferred to what I now call the secondary network. The time has come when we should consider the completion of the process by the transfer of the generators from the secondary network to the primary. The present system of connecting the generating plant to the secondary system is costing us a great deal of money and is open to many objections.

The connection between this point and the present subject lies in the fact that such a system is made economically possible only by the introduction of on-load tap-changing on transformers, which has produced a minor revolution in the outlook of supply engineers. It is surprising that this was not realized many years ago. The first on-load tap-changing regulator was introduced into this country about 1904, but the number of applications of such gear in the following 20 years could probably be counted on the fingers of one hand; not until about 1925 did the on-load tap-changing transformer begin to receive notice, and it was only with its application on the grid system that general acceptance was achieved.

Experience has not indicated that the use of on-load tap-changing on transformers has produced any material reduction in transformer reliability. As regards the cost side, this gear is now available at acceptable figures for large transformers, but there is still important scope for reductions in cost of tap-changing gear for smaller transformers.

In surveying the whole field of voltage regulation one finds that an increasingly important gap still remains. The case of the long, straggly feeder with very light load on a local distribution network, and more particularly on rural or semi-rural networks, is subject to a particular difficulty, namely flickering of lamps caused by voltage variation. Whereas the cooker problem can be met by on-load tap-changing, the problem of lamp flicker cannot; that problem has still to be solved. None of the regulators described by the author gives instantaneous regulation, and, apart from one or two rather limited examples, this is not available. We still require a small regulator which is instantaneous in action, to deal with lamp flicker on domestic networks. There is an alternative solution which the lamp manufacturers might consider, namely to design lamps which have a higher thermal capacity and are not subject to flicker, but I do not wish to suggest going back to carbon filaments. The Hungarian apparatus which the author showed (small house-to-house regulator) is extremely interesting, but it does not deal with the lamp problem.

I agree with the emphasis the author puts on the use of the energy-storing device for operating tap-changing mechanisms, but I am surprised that he considers the flywheel arrangement unsuitable for hand operation, particularly since there are examples of this arrangement in existence.

In Section (4)(*e*) he mentions the desirability of the tap-changing equipment being bolted on to the end of the tank. In most sizes it is possible to go farther and to make the container for the tap-changing equipment in the form of a chamber which is itself a simple extension of the transformer tank.

Although I do not think the author agrees with me, I would stress the view that all switches ought to be outside the tank. We cannot be free, of course, from copper rubbings, even from selector switches, but, apart from this, it is always possible for the timing to go wrong, and I have known cases of carbonization from the selector switches.

The author refers to the inadequacy of the British Standard Specification for tap-changers, and I should like to know whether he has any suggestions to make for its improvement.

One minor trouble which worried us a good deal in the early days was the sealing of vertical and horizontal shafts coming out of oil chambers, and the author's comments on this detail would be useful.

**Mr. E. T. Norris:** The outstanding feature of the devices described in the paper is their extreme complication. A glance at Figs. 19, 22, and 23, bearing in mind that these are all skeleton sketches, explains why the author when summing up the desirable features of tap-changing gear gives as his first aim that everything should be extremely accessible. I think that the most urgent need at present is for on-load tap-changing gear so simple and reliable that accessibility becomes merely a desirable and commendable feature, instead of a first essential. In the designs mentioned in the paper not only the tap-changing gear itself but also the control gear

is very complicated. It cannot be claimed that there is, as yet, a general solution to this problem, but much has already been achieved. The complicated gear and control circuits shown in Figs. 19, 22, and 23, and indicated by the author as being representative, have been greatly simplified in certain recent developments. For example, Fig. 22, showing the author's typical control gear in a simple schematic form, involves approximately 19 sets of contacts, most if not all of which are of the open type and need periodical cleaning and adjustment. Fig. A shows the corresponding diagram* for the control of a mercury-switch on-load tap-changing gear covering the whole range of distribution requirements. A time-delay is incorporated in the mechanism, and instead of 19 sets of contacts there are only 2, and these are contained in a single two-way mercury switch. There are no open contacts. The combination of this control gear with the mercury-switch tap-changing gear results in a complete fully-automatic voltage regulator requiring no periodical attention or maintenance. Operating experience over the last 8 years has proved that tap-changers of the

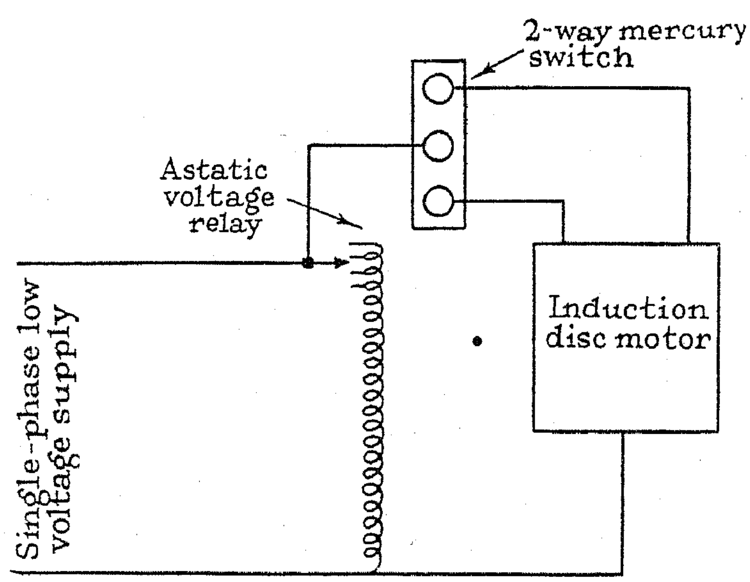


Fig. A.—Automatic control circuit for mercury-switch on-load tap-changing transformers.

mercury-switch type are thoroughly reliable, and this type of equipment is becoming more and more recognized as the ideal for voltage regulation on distribution transformers. The mercury switches involved in the tap-changing are designed to carry with ample factor of safety the maximum possible short-circuit currents under fault conditions, and also to withstand the normal voltage tests to which the associated transformers are subjected.

**Mr. A. T. Chadwick:** The author appears to have some preference for the method of connection shown in Fig. 9(*b*), and I should like to ask him whether he has considered the effect of a system short-circuit on that connection. It might be serious from the point of view of the insulation between the coils of the reactor. I consider that the most attractive system of on-load tap-changing is that which uses the mid-point of the auto-transformer as one of the running taps. This means a larger size of auto-transformer, but it has the advantage of reducing the number of tappings brought from the windings of the main transformer and increasing the number of turns between tappings, so giving the designer much more freedom to produce a mechanically sound tapping-coil construction.

I am disappointed to find that the author does not discriminate between the various available systems of connections; a little critical discrimination would, I think, have been very beneficial. There are also various points of detail, but important points, with which I think he might have dealt, such as the type of contacts—whether knife-switch or butt—used on the various switches, and the speed with which the switches can be moved to get a satisfactory opening. The important question of the design of the auto-transformer might usefully have been considered, and I should like to ask the author what type of auto-transformer he prefers.

Another question which requires some ventilating is the number of operations which can be dealt with by a tapping switch without the mechanism requiring attention. French operating engineers are demanding 10 000 operations before attention is given, and in America 20 000 operations are required. In this country no definite opinion on the point appears to exist, either on the side of the manufacturers or on the side of the operating engineers. Probably we should consider 10 000 operations a reasonable figure on which to base our maintenance periods.

**Mr. C. Ryder:** The ease with which on-load tap-changing gear can be adapted to automatic control has proved something of a boon to supply authorities, and there is no doubt that on many distribution systems automatic regulation of the voltage at certain points possesses distinct advantages. This is because automatic devices can be set to work within prescribed limits and perform their duties with great precision.

The chief device in an automatically controlled tap-changing equipment is the voltage-regulating relay, which is often set to regulate the voltage to within $\pm$ 1 per cent of the normal value. While such close regulation is accepted without question, it reflects credit on modern relays, especially when it is remembered that what is a working limit on the relay is actually a limit of permissible error on first-grade indicating instruments.

With regard to the percentage value of the taps, it is obvious that the finer the taps the less the flickering on lamps when a tap-change is made; on the other hand, a greater number of taps is required for a given percentage regulation, together with a larger mechanism having to work frequently in order to regulate the voltage in small steps.

I should like to know whether any effort has been made to standardize both the size and the number of taps on transformers, as, if agreement could be obtained, it would considerably simplify the problem for manufacturers. At the same time, perhaps the author would be prepared to make some recommendation regarding the setting of the regulating relay in relation to the percentage value of the tappings on the transformer, as a result of operating experience gained during the last few years. Some supply authorities have a preference for setting the regulating relay to about three-quarters of the percentage value of the tappings; in other words, if the transformer tappings were arranged in steps of $1\frac{1}{2}$ per cent the relay would be set at $\pm$ 1·1 per cent, with the object of restricting to a minimum the variation of the voltage

* E. T. Norris: "Astatic Voltage Relay," *Electrician*, 1936, vol. 116, p. 442.

from normal value. It seems to me that the slight gain due to this finer regulation is much more than offset by the increase in the wear and tear on the apparatus owing to the increased number of operations per day.

As an indication of the effect of the voltage-relay setting on the number of tap-changes in a given period, the figures given in Table A, taken from an American publication, may prove of interest.

**Table A**

| Transformer tappings | Voltage-relay setting | Time-delay relay setting | Number of tap-changes per day |
|---|---|---|---|
| per cent | per cent | sec. | |
| 1·25 | 1 | 60 | 8 |
| 1·25 | 1·1 | 60 | 6 |
| 1·25 | 1·25 | 60 | 4 |
| 1·25 | 1·38 | 60 | 2 |

While, in the above results, a fixed time-delay of 60 sec. was introduced to prevent temporary supply fluctuations causing a tap-change, it may be of further interest to record the effect of the length of the delay on the number of operations in the same period, as shown in Table B, which is taken from the same publication as Table A.

**Table B**

| Transformer tappings | Voltage-relay setting | Time-delay relay setting | Number of tap-changes per day |
|---|---|---|---|
| per cent | per cent | sec. | |
| 1·25 | 1·25 | 15 | 84 |
| 1·25 | 1·25 | 30 | 30 |
| 1·25 | 1·25 | 60 | 7·5 |

These figures should be useful to supply authorities as an indication of the value of logging the number of operations against the time relay setting. It is also important to mention that a recording voltmeter connected to the system showed no appreciable change in its indication during the period over which the above records were taken.

**Dr. C. C. Paterson:** Mr. Winfield spoke of the flicker of lamps when cooker loads are switched on to the line, and asked that lamps should be provided which would not respond so quickly. It is rather hard, it seems to me, that a lamp should be required to be an instrument of storage of energy! Perhaps it may have to be so, but unfortunately the newer sort of lamps tend to be even less so than the old. There is, however, another way of dealing with the matter; we could prevent the gulps of current and consequent voltage-kick coming from the switching of cookers. The Cinderella of the kitchen, the heat-storage cooker, is very well able to prevent any gulps of current which may happen through switching cookers on at the end of a long line. There is no need to have any alteration at all of the amount of current taken if a heat-storage cooker is used. I mention this, because the storage cooker does not as yet seem to have " caught on " in this country—although it appears to me to have certain strong points in its favour, of which this is one.

**Mr. S. J. Patmore:** I recently had the opportunity of inspecting a small plant for use in such a consumer's premises as Dr. Paterson had in mind, i.e. on the end of a long rural line, where it was fairly difficult at the heavily-loaded or peak periods to keep the voltage within reasonable limits. This small unit is apparently manufactured in certain standard sizes, and it has a wonderful mechanism which makes it possible to get many changes of voltage with a small number of contacts; it is worked on a similar principle to that shown for the voltage-regulating relay in Fig. 24. I should like to have the author's opinion as to the advisability of putting this type of tap-changing gear into individual consumers' premises.

**Mr. G. G. Morris:** Whilst stored-energy devices for the operation of on-load tap-changing switches may be regarded as an ideal in that if once a tap-change has commenced it is completed independently of any auxiliary supply, they may be considered now to be an unnecessary complication. For instance, with the circuit shown in Fig. 9(*c*) in use, employing a fully rated preventive auto-transformer, it is possible to use a simple direct drive, thus avoiding mechanical complications. If it is argued that smaller equipments are usually hand-operated and that stored-energy devices avoid the possibility of too low a speed of switch opening, then I think that, for small loads, speed of break does not matter very much, always provided properly-designed switches are used as distinct from converted " selectors." The German design illustrated in Fig. 16 shows switches situated in the hottest part of the transformer oil, and from Section 4(*e*)(iii) one gathers that the selector-switch chambers are often in direct communication with the hottest part of the transformer oil. Here are the possibilities of slight distortion of the mechanism due to heat and of seizing occurring between rubbing contacts, especially if these are of the line contact variety where the contact pressure per unit area is high. Separate tanks or compartments should therefore always be specified for the switchgear.

**Mr. E. W. Goodman:** I should like to ask the author what provision he has made for parallel operation of tap-changers. I believe that originally it was thought suitable to couple the tap-changers together mechanically when two transformers were to operate, but this idea seems to have been discarded. Some sort of balanced relay is often used between the two transformers, and, should one transformer get out of step, alarms are sounded or lights lit which warn the operator that the transformers are out of step and need attention. This system at first sight seems very suitable, but, as one practical engineer has pointed out, it is not of very much use in an unattended substation in the middle of Dartmoor, where an attendant may have to cycle 4 miles through 2 ft. of snow to put things right. I should appreciate the author's opinion as to what provision should be made beyond simple alarms.

**Mr. S. R. Siviour:** I should like to re-state a plea which has been made earlier in the discussion by Mr. Winfield, namely for a more instantaneous low-voltage regulator. I am prompted to intervene at this juncture because it may be thought, after Mr. Paterson's remark, that a solution has been found in the form of the thermal-storage cooker. It is not only a question of cookers,

however; we have to deal with trouble caused by motors, which it is quite impossible to cure with any of the available types of regulator. We have, for example, numbers of complaints from consumers in the vicinity of quarries where motors are employed.

**Mr. W. Parry** (Stafford) (*communicated*): With regard to parallel-winding circuits (page 334), it appears that if a short-circuit on the line occurs at the instant when only one half of the winding is in circuit (i.e. during a tap-change), the heating effect is four times that for the complete winding, and with suitable conditions this extra heating could seriously damage the winding.

The single-winding circuit in which the reactor bridges two tappings of the transformer and so gives a voltage midway between them, has many advantages from the point of view of design of the transformer with regard to the bringing-out of tappings. It uses the minimum number of tappings and outgoing leads, and this in itself increases the reliability of the transformer. Further, in large transformers, owing to the high volts-per-turn of the winding, it often happens that the number of turns between tappings is small and it is difficult to make suitable tapping coils. With this method there is a maximum number of turns between tappings, and the coils can usually be so arranged that taps are taken from outside joints only, which is a very desirable feature.

Turning to the subject of mid-point reactors (page 335), from the magnitude of the magnetizing current mentioned it appears probable that there is an air-gap in the core of the reactor. What are the author's views with regard to using reactors with cores having no air-gaps, for conditions where the load current only flows through half the reactor during a tap-change?

Regarding hand operation, as the handle has to be used on the intermediate driving shaft it appears that something like 20 turns will be necessary per tap-change. This is a very tedious operation, and it would be an advantage to arrange the handle to fit on the driving shaft O in Fig. 19.

It would add to the value of the paper if a complete typical diagram were given for a more complicated scheme than that shown on page 344—such as for automatic parallel control of two transformers. As tap-changers are expensive, it is as well to let purchasers know that they are getting some real engineering for their money.

It is clear that increasing the time-delay will decrease the number of operations of the tap-changer, but the best value to adopt can only be decided for each particular case. It would be of great interest if the author could include a typical curve showing number of operations per day against time-delay settings whilst still keeping voltage variation within allowable limits.

All his illustrations of English transformers show the selector switches in oil separate from that of the main transformer. There appears to be no essential reason for this, unless it is a question of ease of inspection. What are the author's views on this point?

What is his experience with regard to the frequency of inspection of (1) selector switches, (2) diverter switches, compared with the number of tap-changes made?

**Mr. R. R. Pattinson** (*communicated*): It is no doubt true to say that manufacturers in this country did not consider seriously, until after the War, the question of changing tappings on load. I know one Continental firm, however, who produced regulators fitted with on-load tap-changing as long ago as 1904, and in many respects the design differs little from that of the modern types.

It is interesting to note that considerable reductions in weight have been effected during the last few years. As an instance of this, a driving mechanism fitted to a regulator in 1927 weighed as much as 23 cwt., whereas the weight of a modern mechanism of the same make would be about 6 cwt.

On page 339 the author makes reference to one complete turn of the handwheel effecting a single-tap-change. It seems very desirable from an operating engineer's point of view to adopt this as a standard, and thereby avoid errors which are likely to arise on systems where more than one make of regulator is in use. I have known of cases where up to 40 turns have had to be made in order to change from one step to the next.

The use of mercury switches has extended rapidly during the last few years. Care should be exercised, however, to ensure that the switches have the necessary rupturing capacity under fault conditions and are made of a suitable type of glass, or reinforced internally by a ceramic sleeve in the vicinity of the electrodes. Experience has shown that it is bad practice to allow the switches to open only under the action of gravity, as they are likely to stick with disastrous results, and I suggest that means such as follow-up cams should always be provided to open as well as to close the switches mechanically.

The induction disc motor as a means of driving tap-changing mechanisms is worth careful consideration, as it renders limit switches unnecessary and will not burn out if stalled. The condensers which are associated with this type of motor have been a source of trouble in the past, and manufacturers should carefully investigate the circuit conditions before deciding on the type of condenser to be employed. I recall an instance when transient voltages of the order of 1 200 volts appeared in a circuit which was normally operating at 250 volts.

With regard to the author's remarks on the position of the limit switches, there is little doubt that the right position for such is directly in the motor circuit. Even contactors with throw-off devices have been known to stick, and the consequent overrun as a rule results in extensive damage to the driving mechanism.

The author refers on page 345 to the practice of arranging for regulators to run to the lowest boost position. Whilst this is certainly preferable to the regulator remaining where it is, it has disadvantages when the tapping range is a large one, and I suggest that running to the "No boost" position is the better arrangement.

In the early days much trouble occurred owing to "freezing" of the contacts of voltage-regulating relays. The recently-developed "Astatic" voltage relay overcomes this difficulty by the use of a mercury switch, but there are many manufacturers who still adhere to the open contact. Condensers and resistances shunted across the contacts have considerably reduced the sparking at the contacts, but there still remains the problem of deciding which is the best metal to use for them. Many metals have been tried, with varying degrees of success,

but silver seems to be the most satisfactory. Perhaps the author would let us have the benefit of his experience in this connection.

The advent of the regulator on low-voltage networks has produced complaints of radio interference, and investigations have shown that the interference may be generated at the contacts of the voltage relays. I would suggest that radio-interference suppressors should become a standard fitment on all such pieces of apparatus.

One of the problems with which the operating engineer is faced is that of carrying out adjustments to the setting of voltage relays. Frequently this entails removing the front of the relay and adjusting some delicate balance or spring mechanism. When the fingers are cold the instrument is likely to suffer, and the solution is for the manufacturer to provide some simple means of adjustment external to the instrument. If this adjustment were calibrated in terms of "outgoing volts" the engineer would not need to use a voltmeter. It is realized that there are certain objections, but even if the voltage indicated is not accurate the scale will give some indication of the sensitivity of the adjustment.

Complaints are sometimes made about low-voltage conditions on a network to which is connected an automatic voltage regulator. An examination may reveal that the regulator is working satisfactorily, and it can only be assumed that it ceased to function for some time and then corrected itself. Except by installing recording voltmeters, which is expensive, there seems to be no method of checking a regulator's operation. A counter certainly gives some indication, but will not satisfactorily cover the case cited above. The author may be able to provide a solution.

Of the various electrical position indicators which are available I have a distinct preference for the phase-shifter type as being more accurate than the potentiometer type, which in many cases seems to be affected by temperature.

The author makes reference to boosters of the current-actuated and voltage-actuated types. Neither type completely fulfils requirements. The applied voltage in rural areas cannot be considered constant, and the current-operated regulator may at times alter the voltage which is already beyond the statutory limits. Similarly the voltage-operated regulator takes no cognizance of the load drop. I would therefore draw the author's attention to a small regulator covered by British Patent Specification No. 433904, which combines the functions of the two types. It is a fully automatic two-step regulator which works in conjunction with an off-load tapping switch. This latter switch caters for seasonal voltage-changes, whilst the regulator provides two steps of boost from the voltage determined by the position of the tapping switch. If the incoming voltage is high the current-actuated element is rendered inoperative and can only operate after the outgoing voltage has dropped to a predetermined figure. The simplicity of construction of the regulator should make for low first cost and give it a wide appeal.

[The author's reply to this discussion will be found on page 361.]

## NORTH MIDLAND CENTRE, AT LEEDS, 2ND MARCH, 1937

**Mr. W. T. J. Atkins:** There can be no question as to the importance of on-load voltage regulation to the supply industry; in fact, I think it would be safe to say that without equipment of the kind described in the paper the modern technique of interconnection would be quite impossible.

The author makes a number of what appear to me to be artificial distinctions when he speaks of the fields of application of tap-changing gear. I am unable to see what essential differences exist between the operations described in Sections (2)(*d*), (2)(*e*), and (2)(*f*). They appear to me to be different aspects of one and the same thing.

It is desirable that we should try to make some generalizations regarding gear of this kind, and the most outstanding generalization seems to be that tap-changing gear should be a sound mechanical job. Such details, for example, as the question of oil leakage through bushings are largely mechanical matters and they are the points to which very considerable attention should be given if equipments are to be trouble-free in service.

I should like to plead for the use of resistances, rather than chokes, as bridges between the tap positions. In the first place, when chokes are used there is a remarkable change in effective impedance of the transformer during a tap-change. The reactance of the bridging chokes is added to the normal reactance of the transformer, and it is possible that transitorily the impedance may be very nearly doubled. The author rather evades this question by saying that it does not matter. Nevertheless, the effect is there, and it may very well be that it is only free from causing embarrassment in those instances where the tap-changing is rapid. It is quite a common experience to notice a big swing on meter needles during a tap-change where the effect exists. If the tap-change takes place quickly the needles do not have an opportunity to follow, but the effect is there all the same, and can be demonstrated by means of an oscillograph. Another drawback to the choke bridge is the possibility of saturation, particularly if solid cores are used. Furthermore, third harmonics may be generated, with disastrous results on occasions, and there is also the question of abnormal voltages at the contacts of the series switches. Effects of this kind also occur, of course, with resistance bridging, but not to anything like the same extent. Taking, for example, the variation of impedance during tap-changing, with resistance bridging the effect is not so marked because the resistance added to the reactance of the transformer does not greatly increase the impedance. It is true that there is a corresponding voltage injected into the circuit, but since its phase differs by 90° in this case the effect can be shown to be not so disturbing.

There are, of course, drawbacks to the use of resistances, one of them being that with certain methods of construction twice the number of tappings off the windings may be necessary. Another point is the need for the stored-energy method of driving. I believe that this method is desirable in any circumstances, and so far as heat dis-

sipation is concerned there need be no real difficulty if the tap-change is carried through sufficiently quickly. It is quite practicable to design the gear with sufficient dissipation to allow tap-changes to occur in reasonably rapid succession and yet meet all other conditions.

**Mr. C. J. Sargeant:** I should like to ask the author whether he has satisfied himself that mercury switches are suitable for use on on-load tap-changing equipments. I have had some experience with mercury switches, and this indicates that their life is somewhat indefinite: some mercury switches will operate thousands of times, and others only a few times, before bursting. It is this uncertainty that I do not like, as it would be disastrous if such a switch burst on a tap-changing equipment. No amount of inspection can safeguard against this.

There is another point regarding the mercury switch which has to be carefully watched, and that is the possibility of the mercury being strangled or pinched by the field set up by heavy currents, such as may occur on short-circuits on the system. At approximately 20 times the rated current of the switch the field set up is strong enough to split the mercury bridging the contacts into two, thus causing an open circuit. In order to guard against this it is necessary to use a mercury switch of approximately 10 times the current rating.

I should like to know whether the author has any experience of, or tests to show the merits of, the oil-switch type of contacts where the moving contacts drop vertically downwards, as compared with the contactor type where the moving contacts move practically in a horizontal plane. I believe there is a good deal more wear and tear on the oil-switch type than on the contactor type, owing to the fact that the arc is not so free to clear the contacts.

I regard as unnecessary the rather complicated mechanism shown in Fig. 19, which is used to declutch the motor. Certain manufacturers who made a similar type of gear many years ago dropped it in favour of a simple mechanical stop. The mechanical stop only comes into operation under emergency conditions, as normally the limit switches prevent running beyond the limits. If the emergency arises, the motor is amply protected by the thermal overload relay against burn-out when stalled. The limit switch is a reliable piece of mechanism and is used on more important apparatus than tap-changing gear, where it is solely relied on.

I do not understand why the author advocates connecting the limit switch in the contactor-coil circuits rather than direct in the motor circuit, and I do not agree that if it is placed in the motor circuit it involves more critical timing. If anything, the timing is less critical in this case, owing to the fact that the time taken for the contactor to open the motor circuit (after the limit switch has de-energized the coil circuit of the contactor) is eliminated, and the protection is better, as the possibility is eliminated of trouble due to the contactor sticking. The possibility of trouble due to the limit-switch connections being reversed is the same whether the limit switch is connected in the coil circuit of the contactor or in the motor circuit.

On page 343 the author says that "The tap-changer should preferably be built as a complete unit which is bolted to the transformer tank, so that all parts are readily accessible without disturbing the transformer." Exactly the same thing is accomplished by making the tap-changing gear an integral part of the transformer, as shown in Fig. 15(*b*). It would appear that in the event of trouble the maintenance staff would much prefer to handle a piece of apparatus weighing a few hundredweights rather than one weighing several tons. If the gear is built as shown in Fig. 15(*b*), only that portion of the equipment which is faulty has to be removed, and after removal temporary connections can be made, so that the transformer can be operated on a fixed ratio after the oiltight joints have been remade and the compartment has been refilled with oil. If the tap-changing gear is built as a complete unit and bolted to the transformer tank, should any portion of the gear develop a fault it is necessary to take the complete gear away. In order to put such a transformer back into commission, after making temporary connections, it is necessary to fit a temporary cover over the terminal board and to fill the space between the terminal board and temporary cover with oil.

**Mr. L. F. Southorn:** The author describes 3-phase tap-changers operating on the primary side of the transformer, and 3-phase booster regulators. These are both satisfactory provided that the load is evenly balanced between the three phases, but where there is a considerable amount of out-of-balance at certain periods it may be preferable to regulate each phase separately. This has been done by installing a single-phase booster regulator on each phase of a distribution transformer, and this method, although costly, may be the only satisfactory means of providing good regulation in such awkward cases.

Auto-transformer regulators have a disadvantage in that on one tapping the particular switch contact is directly in the line circuit and is subject to the maximum system short-circuit current at that point, there being no added regulator impedance to protect that contact. With a booster regulator the switch contacts are not in the line circuit and they are protected by the impedance of the windings; also, in the event of any trouble, it is usually possible to isolate the regulator and give a supply direct. The latter is not a very important point, as modern tap-changing gear is now proving its reliability.

The author describes certain switches as "transfer switches." One also hears them described as "step switches," "series switches," and "diverter switches"; there seems to be a case for the adoption of a standard term to describe this part of the equipment.

Fig. 23 shows an interesting voltage-regulating relay and time-delay relay in which the spindle is supported on two leaf springs. I should like to ask the purpose of the disc and the small magnets situated at the top of the spindle.

As regards the question of mercury-switch regulators, it is important that the switches should be rated on the maximum possible short-circuit current, with a generous margin to ensure that there is no danger of the pinch effect occurring under this condition. The majority of the various regulator mechanisms appear to be complicated and to contain many component parts. I suggest that there is a call for a more simple type of mechanism and that there is still room for improvement in this respect.

**Mr. A. C. Bailey:** From an operating point of view it would be an advantage if transfer switches were always placed in drop-down tanks, instead of in compartments with side covers. Where a circuit breaker is installed in such a compartment the oil becomes carbonized and has to be changed from time to time. It is a long job to take off a side cover, clean the chamber, and replace the cover, making an oiltight joint. With a drop-down tank, on the other hand, it is quite a simple matter to effect a change of oil.

**Mr. R. M. Longman:** It must be pointed out that voltage regulators are not a cure for all regulation troubles—they cannot take the place of copper. I remember a case where some consumers were connected at the end of a long light overhead line and the voltage regulation was bad; an induction regulator was placed near the load and—thanks to its exciting current at low power factor—its effect was to make the regulation worse. I consider that the transfer or diverter switch should be installed in a separate tank from the remainder of the gear and provided with a drop-down tank to facilitate quick inspection. Further, there should be no moving contacts inside the main transformer tank.

It is essential that all tap-changing mechanisms should be mechanically sound and as simple as possible. The correct metal must be used for all parts subject to wear, and such parts must be arranged so as not to affect the accuracy of the contact. Mechanical limit switches must be provided, in addition to the electromagnetic type. A new application of tap-changing mechanism is to the starting of large motors, a field of use which is likely to be considerably extended. With reference to the application of tap-changing gear to existing transformers, it may be cheaper in the end to provide new transformers complete with the voltage-regulating equipment.

Turning to page 347, where the author discusses electrical position indicators, I would point out that the inductive potentiometer is a transmitter providing an open-scale instrument and is capable of many uses, such as level indication.

**Mr. A. G. Smith:** Where a 3-phase motor is used for operating tap-changing gear it is important that a triple-pole overload protection device be used. In a recent case a motor was burnt out owing to the irregular operation of a single-pole thermal cut-out. The two remaining cut-outs were left intact, and carried sufficient current to damage the motor over a lengthy period. This incident raised a further point. It happened that the tap-changing gear was left inoperative at about the midway position. Had the trouble occurred at a time of low input voltage the excessive secondary voltage, due to the fixed ratio, might have caused damage to consumers' apparatus when the input voltage rose. A means of avoiding this danger appears to be necessary where automatic tap-changing gear is installed in unattended substations.

**Mr. F. S. G. Hinings:** While resistance bridging of taps is quite feasible on small transformers, on large transformers it is impossible to dissipate the heat due to the losses in the resistances if the resistances are left in circuit owing to faulty operation of the gear. Even though the driving mechanism is designed to use stored energy—in the form of a spring, flywheel, or falling weight—to operate the gear, the best design may fail sometimes owing to normal wear or to lack of maintenance. Unless protective devices are installed, which will take the equipment out of service if a fault develops, there is a great danger of fire. On the other hand, if continually-rated reactors are used for bridging the taps, no harm can come to the transformer should faulty operation of the tap-changing gear take place, as the heat due to the losses in the reactor can easily be dissipated. The extra complication of the protective relays is therefore unnecessary.

To illustrate the above, consider a 30 000-kVA 132-kV transformer, having 1·43 per cent steps, as installed on the grid. The transformer losses are approximately 300 kW, the full-load current is 131 amperes, and the voltage per tap is 1 100 volts; so that, if the current in the tap section of the winding is limited to full load when bridged by the resistance, the loss in the resistance when in circuit is 145 kW per phase, i.e. 435 kW per 3-phase transformer. The radiating surface required for dissipating the losses in the resistance is therefore greater than that required for the transformer. The losses in the continuously-rated reactor for the above transformer are about 10 kW, which small loss can easily be dissipated.

**Mr. I. H. Hedley:** I should like to make a plea for simplicity in tap-changing gear, and to point out the advantages of the resistance type of equipment from that point of view. Reactors have to be designed to avoid saturation which would produce harmonics, and to obtain the necessary impedance value. Compromise between the various factors involved has led to the diminishing use of the centre tap of reactors as a permanent tapping position. Reactors are now mostly used only for changing from one tapping to another, in a similar manner to that in which a resistance is used, and I would prefer a resistance wherever possible.

Selector switches have to be made with one common point, usually in the centre, and better and more simple contacts would be possible if switches similar to most "off load" types could be used. In the latter the connection is made between adjacent contacts, and no current has to be taken to a centre point. What does the author consider to be the maximum capacity of selector switches when series switches are not used?

[The author's reply to this discussion will be found on page 361.]

## NORTH-WESTERN CENTRE, AT MANCHESTER, 16TH MARCH, 1937

**Mr. J. S. Peck:** I have watched with interest the development of on-load tap-changing gear during the last few years, and have wondered why it was that, although we knew more than 40 years ago all the fundamental principles governing the problem, we did not reach anywhere near the position we have reached to-day. The original a.c. regulator or booster was invented by L. B. Stillwell nearly 50 years ago, and contained most of the essential features of the regulator of to-day. It was similar to the arrangement shown in Fig. 2(*a*), except that

the primary of the booster transformer was connected across the line, and the secondary (which was the tapped winding) was connected in series with the line. A tapping switch was used with a face-plate controller. The moving arm on the tap switch was split, and between the two parts was connected a reactance coil, the mid-point of which was tapped in exactly the same way as is done to-day. Hundreds of these regulators were supplied all over America for feeder voltage control. The trouble with the face-plate regulator was that above a certain current, and above a certain voltage per step, sparking and burning of the contacts resulted. Therefore its use was limited to rather low current and voltage values.

The next step was the arrangement shown in Fig. 2, where the auto-transformer was used and the secondary of the busbar transformer was connected in a line exactly as it is shown here. The same arrangement of face-plate as before was used, but it was possible with this arrangement to reduce the current handled on the face-plate. The principal use to which the type of regulator in Fig. 2(*a*) was applied was in connection with rotary convertors where, in order to obtain a variable d.c. voltage, it was necessary to vary the a.c. voltage supplied to the convertor. The usual practice was to supply the primary of the boosting transformer from tappings brought out from a special coil in the main transformer, and many useful and ingenious combinations were worked out in order to reduce the number of tappings required on the face-plates. Two face-plates were used for boosting a 3-phase circuit. Many of these were supplied in connection with rotary convertors, until with the gradual increase in the size of convertors the capacity which could be handled on a face-plate was exceeded; and this arrangement was gradually replaced by the induction regulator and the synchronous booster.

In the late 'nineties an order was received for what was then a very large transformer, about 1 000 kW, with a secondary voltage range of more than 2 to 1. It was further specified that the voltage-change should be gradual, i.e. without jumps. To accomplish this, tappings were brought out from the primary winding of the transformer, and an induction regulator used for working between the tappings. This is precisely the arrangement shown in Fig. 12. It worked quite satisfactorily, but the mechanism for coupling the regulator to the face-plate was rather complicated and costly.

I think the reason why more progress was not made in those early days in the development of tap-changers was because the market did not require them. The induction regulator for a long time practically displaced the face-plate type of regulator for feeders and rotary convertors, but with the greatly increased size of transformers and the necessity for interconnecting power systems it became necessary to apply tap-changers to very large transformers. By this time contactor gear and oil circuit-breakers had reached a high state of development, and the possibility of using them soon became apparent.

The biggest step made was in using a circuit breaker, or a contactor, to interrupt the circuit while the change from one tapping to another was made. Fig. 9(*b*) shows what might be called the "brutal" way of effecting the results, with a circuit breaker in each tapping, so that by alternate closing and opening a change can be made from one tapping to another. The arrangements shown in Figs. 9(*c*) and 9(*d*) are logical solutions of the problem, and, in various forms, are in common use to-day. But I think the arrangement shown in Fig. 11(*c*) may have a very considerable application.

In the very early days we tried substituting resistances for reactance coils for bridging between the tappings, but they required a quick-break device for changing from one step to the next one, and this complicated the design. However, with the greater experience in the design of mechanisms which we have to-day, the scheme shown in Fig. 11(*c*) seems quite feasible.

It is remarkable that tap-changing should have so developed in recent years that it justifies the employment of engineers who specialize in this single branch of the business. A number of very ingenious and successful mechanical and electrical devices for tap-changing have been developed, and, while there have been minor troubles, in general the results have been very satisfactory. Improvements are being continually made, and tap-changing gear is very rapidly approaching a condition where it may be considered almost as reliable as the transformer itself.

**Mr. E. T. Norris:** Regarding the author's condemnation of the parallel-winding method (page 334), his first criticism that the best conditions for circulating-current and voltage variation during a tap-change are contradictory applies equally to the choke-coil method, as he himself states on page 335. His second criticism, that protective relays are necessary to protect the windings from overload under certain conditions, applies equally to some other methods, as the author himself states on page 331. His third criticism, that there is a risk of interruption to the supply if a tap-change is incompleted, applies equally to the choke-coil method for many other reasons, and is responsible for much of the complication described on page 340. These characteristics are in each case mentioned in the paper merely as interesting features of the design when referred to the choke-coil or other methods, but are given as condemnatory criticisms of the parallel-winding method. Why this different treatment for the parallel-winding method?

The characteristic peculiar to the parallel-winding system which the author possibly had in mind is an uncompleted tap-change due to failure of the supply to the operating motor during that tap-change. This risk is too remote to need consideration, as a tap-change lasts only a few seconds. Mr. G. L. Porter has shown that on the basis of probability it will occur once in 864 years. In support of this estimate, operating experience over the last 10 years with transformers ranging from 2 000 to 75 000 kVA has not produced a single instance of such failure. On the other hand, with the choke-coil method an uncompleted tap-change due to other causes much more probable in practice may result in serious damage as well as interruption to the supply. A switch sticking in or sticking out, a broken switch-arm, welded contacts, a damaged cam, a broken gearwheel, or other mechanism failure, are typical examples. These are not mentioned by the author, even as interesting features of the design, in connection with the choke-coil method, whilst a much more remote contingency is emphasized as a condemnatory criticism of the parallel-winding method.

Again, why this different treatment for the parallel-winding method?

The author implies that the parallel-winding method is dead. Actually, over 3·5 million kVA of gear embodying this principle—a good proportion of the total output in this country of on-load tap-changing gear—have been manufactured during the last 10 years, and all are giving satisfactory service. The parallel-winding method in its sphere of application is simpler than the choke-coil method, both in principle and in construction; tappings from the inner windings of the transformer are unnecessary, and the external connections are simpler. Moreover, an exhaustive series of tests both in the laboratory and under operating conditions involving high voltage stresses and extensive switching operations over wide areas at 132 kV have proved that no dangerous internal stresses, either of voltage or of current, occur in the windings under any operating conditions. These tests confirm the widespread operating experience referred to above.

**Mr. J. L. Carr:** The author refers to the application of voltage regulators, and mentions a very interesting development in Hungary of a small automatic booster transformer at consumers' terminals. Devices of this sort might have limited application in extreme cases, but, in my view, only as an expedient. The most satisfactory method of application of voltage-control equipment depends to a large extent upon the distribution arrangements. With low load densities on systems employing medium-voltage feeders, the centralized installation of voltage-control apparatus may give reasonably satisfactory results; but, as the load density increases, the results will be less satisfactory if the distribution conditions are not altered. In more densely-loaded urban districts where distribution networks are employed, and high-voltage feeders used to the exclusion of medium-voltage feeders, with transformers spaced more closely as the load increases, centralized control of voltage at the main substations (33/6·6 kV) may give satisfactory results. The heavier the load density is over the area so controlled, and the more uniform are distribution feeders as regards dimensions and loadings, the more satisfactory will be the results.

With a more straggling layout similar results cannot be achieved, and it may be necessary to install voltage-control equipment at more remote points and, in extreme cases, even at the consumers' premises. The cost of voltage-regulating gear, proportionate to the power controlled, increases rapidly as the size goes down. If voltage regulators are to be installed at a large number of scattered points, the total cost is likely to be very high. Moreover, these devices require regular inspection and maintenance. Manufacturers' representatives have stated that inspection is necessary at least once every 1 000 tap-changes: the author's views on this statement would be appreciated. The number of changes an automatic booster or tap-changing transformer will perform depends to a considerable extent upon the closeness of regulation required, and also upon the load characteristics. The author mentions that by increasing the setting of the time-delay relay from 30 to 60 sec. the number of tap-changes performed can be reduced by 75 per cent. Some 3–4 years ago the average changes on one system approximated 85 a week: as load conditions altered, the number of operations increased to 200 a week in some cases. With operations of the order of 200 to 300 a week, a careful inspection every 1 000 operations, which means taking the apparatus off load, results in maintenance becoming rather a serious matter.

With regard to the setting of the time-delays, a great deal must depend upon the load conditions. In some cases, where the initial time-delay settings were about 60 sec., reduced settings of 15 sec. have been adopted in order to give improved voltage conditions. In these positions considerable load-changes occur at definite times, so that a certain number of operations are necessary, irrespective of time settings.

On page 335 the author refers to transition steps on the reactor in order to give closer gradation of the voltage; but generally, if the tappings are not more than $1\frac{1}{2}$ per cent, and preferably nearer 1 per cent, there is no necessity for closer gradation.

One type of voltage-control relay was a source of continual trouble in that it would not maintain its calibration for considerable periods. More recent relays mentioned have given improved results; but experience with these types is somewhat limited.

The loading of voltage-control relays is rather heavy, and the effect on the voltage-transformer ratio is quite appreciable. I would suggest the possibility of shunting these relays by condensers, so as to reduce the volt-ampere loading and consequently the disturbance of transformer ratio.

Since 1934, 4 cases of failure due to trouble on selector switches have been reported, and 7 cases of mal-operation of the mechanism. In addition, considerable burning of transfer-switch contacts on heavy-current boosters has been experienced. Whilst the number of faults does not appear excessive, it is considered higher than necessary.

**Mr. A. G. Ellis:** It would be useful if the author would give a general statement indicating the limiting voltages and current ratings of the various kinds of switch and driving mechanisms, as classified in Section (4) of the paper. I will give a few figures which perhaps he will be good enough to amplify in his reply.

Broadly speaking, the direct-driven switch, operated by motor and gearing [Section (4)(*a*)], is used on transformers up to the largest capacities. The selector switch, of which the author showed a model, is used for the heavy type of tap-changing equipment, and has already been applied for currents up to 1 200 amps. in connection with 132 000-volt transformers with directly earthed neutral.

Operation by stored energy [Section (4)(*b*)] is limited to the small and medium-size types of transformers up to about 4 000 kVA. Reference is made to stored-energy arrangements embodying falling weights and flywheels, and I should like to ask the author what is the present limit of ratings and sizes of these types. Spring-operated switches constitute a compact and economical solution for medium ratings, because it is possible to combine the selector switches and the transfer switches into one switch mechanism.

In the smaller ratings the mercury switch [Section (4)(*c*)(iv)] has a field of application. The unit mercury

switch also combines in itself the function of selector and transfer switch. The limit of current rating of the mercury switch is the short-circuit current which it will withstand without turbulence or explosion. Such switches are available for short-circuit currents up to 900 amps.; that is, they are suitable for a normal current capacity of about 50 amps. at 11 000 volts, which would serve for a 3-phase delta-connected transformer winding up to 1 500 kVA. While mercury switches have given satisfactory operation and offer an economic solution for small transformers, the idea of the power supply from a 1 500-kVA transformer depending on a small glass bulb of mercury does not always commend itself to power supply engineers.

Regarding the circuits classified in Section (3), when I visited the U.S.A. some 10 years ago, and investigated the question of on-load tap-changing, the parallel-winding scheme [Fig. 9(*a*)], which had been tried out, was being superseded by the single-winding scheme [Figs. 9(*c*) and (*d*)]. The reasons are given in the paper, and the single-winding scheme is now practically universally used.

Turning to the question of the use of a preventive resistor as against a reactor, a resistor is attractive because it is much smaller than a reactor for the same duty. Reactors in the large tap-changing transformers are of considerable bulk and have to be squeezed into a relatively small space. But the reactor has an advantage in that the mid-point of its winding can be used as a running position to give intermediate voltage-steps between the adjacent winding tappings: the number of voltage steps obtained is thus double the number of winding tappings. This is of considerable advantage in designs involving high voltage and/or heavy currents. In this respect, the resistor has certain limitations, and its effective field of application is in medium and small transformers with relatively few voltage-steps. The preventive reactor can be so constructed as to be suitable for continuous operation, but to make a resistor for this purpose for continuous rating, so that it would not burn out in the event of the switch jamming and leaving the resistor in circuit for a longer time than the transition period, is uneconomical, if not impracticable.

Of the desirable features of design given on page 343 in our work we have consistently adopted (i) and (ii) since commencing the development of modern ironclad equipment some 10 years ago.

I should like to call attention to Section (5), where the author refers to a very important point regarding impulse voltages on tap switches. It must not be inferred from that paragraph that tap-changing equipment cannot be designed and built to withstand impulse-voltage tests. The 50-cycle tests specified in the British Standard Specification for Power Transformers do not profess to cover impulse-tested transformers, and this applies to both the transformer windings and the tap switches. Impulse-tested transformers are subject to special impulse tests of values which are at present under standardization, and in such cases the transformer complete with its tap-changing gear is subjected to the impulse test, the tap switches being designed and constructed accordingly.

**Mr. W. L. England:** On page 331 the author says it is not generally possible without considerable expense and difficulty to add tap-changing gear directly to an existing transformer. Actually it is a very simple matter in many cases to add automatic on-load tap-changing gear to existing units, irrespective of whether the manufacturer of the gear is also the manufacturer of the transformers. On units of 250 kVA to 1 000 kVA the only modification to the existing tanks necessary when on-load tap-changing gear is added is an increase in the height of approximately 20 in. It will be seen, therefore, that after the transformers have been modified they can be replaced in their original substations, since there has been no increase in plan dimensions. Further, the fact that the on-load gear has been added does not mean that it is in an inaccessible position.

On page 336 the author refers to some means of bridging tappings, one of them being the induction regulator. It will have been gathered from the paper that one of the main bugbears of tap-changing is the circuit-breaking switch, and any device which can be produced to replace this is a great advance on general present-day practice. Recently there has been developed an apparatus which can be connected across the two extreme tappings of a tapped winding and will give smooth voltage variation over the whole range, no circuit-breaking switch being involved. I refer to the moving-coil regulator, which has been fully described elsewhere.

A comprehensive description of a two-step booster is given on page 347; this booster arrangement, I believe, was first suggested by Mr. G. L. Porter. I wish the author had stressed the main reason for the particular winding arrangement, which is that the apparatus has no loss at no load—a very important fact when dealing with small distribution loads.

**Mr. S. R. Mellonie:** To the author's list of desirable design features I would add: (1) The elimination of packed glands for horizontal shafts entering chambers below the oil-level. (2) That all protective devices should "fail to safety."

Operating experience with tap-changing equipments has been generally satisfactory. The troubles that have occurred have not been major troubles with switchgear or transfer switches, but have been connected with the control gear. One particular equipment has completed 28 000 tap-changes in $3\frac{1}{4}$ years, and during that time no contacts have been renewed but the oil in the transfer-switch tank has been changed twice. This particular unit is one of two operated in parallel. When only one transformer was in commission on automatic operation, the average number of tap-changes (1 per cent) per day was 20, and with the second unit in parallel the number dropped to 16, thus decreasing the wear and tear of the two units by a considerable percentage. Another equipment has operated 20 000 times in 6 years. This one has $1\frac{1}{4}$ per cent taps and, while the oil has been changed twice, considerable wear has taken place on the contacts. This equipment is of the resistor type shown in Fig. 11(*a*) and is not fitted with transfer switches.

On page 331 the author suggests there are advantages in not operating these equipments in parallel. I would suggest that, where duplicate equipments exist, full advantage is obtained by working them in parallel because this gives maximum reliability of supply, ensures equal division of the load, and improves the regulation. The author's argument with regard to switchgear is quite

sound, and I would suggest that it is good practice to base the size of the transformers and, to some extent, the reactances, on the economic rating at which the switchgear can be purchased.

With regard to the control of load distribution in parallel circuits with different time-constants, an allied problem arises where two transformers of the same impedance but differing copper losses are paralleled. In such a case with normal values of resistance and reactance the copper losses can vary as much as 100 per cent without increasing the transformer currents by more than 1 per cent.

**Mr. C. Ryder:** It is to be regretted the author does not make more detailed reference to the control of on-load tap-changing, in order that full advantage may be taken of a piece of apparatus which enables us to adjust the voltage of a transformer while still on load. The control of a single transformer is very simple, but cases arise in practice where two, three, or even four equipments are to be run in parallel under the control of one automatic regulating relay. Some amplification to the control apparatus is therefore necessary to ensure that the transformers remain in step.

While the control scheme can readily be adapted to fulfil these conditions it would seem that unnecessary complication is brought about by supply authorities specifying that the gear must operate in any prearranged sequence and that it must be possible to take out of service any one of the units for local operation and to arrange its re-introduction into sequence automatically. I should be interested to know whether the author can give any information regarding the number of tap-changer units it is possible to control in this manner in one substation before it becomes economic, on the grounds of simplicity and ease of maintenance, to substitute one or two larger units and remove the smaller ones to other sites.

The two rather interesting schemes of regulating relays using tuned circuits appear to simplify the matter of regulation, but on the other hand I should like the author's opinion as to the variations in sensitivity likely to be experienced due to the variations of the frequency of the supply.

There are a number of factors which have an influence on the volt-ampere burdens of regulating relays. Among these may be mentioned reduction of changes due to temperature variation, and the magnitude of the working forces on the plunger, which, of course, influences the contact pressure. It is also desirable that the movement should be robust and that any frictional forces to be contended with should be small compared with the operating torque. The average burden of a voltage-regulating relay is generally between 25 and 50 volt-amperes, and in view of the fact that voltage transformers generally have a capacity of 100–200 VA it would appear that the relay burden should not cause much difficulty.

Criticism of the control scheme shown in Fig. 22 has been made on the ground of complication, a comparison being made with the simplest arrangement in which the regulating-relay contacts are connected directly to a small motor on the transformer mechanism. Comparisons of this nature are not helpful unless the operating characteristics are reduced to a common basis, and the apparatus is made to perform similar functions. It may be of interest to record that many equipments embodying the simple arrangement advocated have been put into service, the arrangement consisting of the top half of the relay shown in Fig. 23, with the contacts connected directly to the motor controlling the tap-changing gear. This arrangement, however, is only possible with relatively small transformers and where specific conditions regarding adjustable time elements, etc., have not to be met.

In connection with the relay shown in Fig. 23, one very interesting feature might have been stressed a little more, namely the frictionless suspension of the plunger. Quite a lot of attention has for some years been devoted to regulating devices in attempting to minimize the amount of maintenance required and to reduce the effect of friction of moving parts upon sensitivity. It is generally agreed that where friction occurs it is very difficult to control variations due to changes of temperature and humidity, and experience has shown that bearings of moving parts must continually be kept clean if the original sensitivity is to be maintained. Relays embodying a moving core which works in either a guide or hinged bearings suffer from this disadvantage. On this account the design of relay shown in Fig. 23 represents a definite step forward, since all friction has been eliminated by suspending the plunger on leaf springs.

**Mr. A. W. Needham:** In many cases, particularly in rural districts, the voltage-drop is the factor which limits the load capacity of a cable. The copper may carry more than it should be allowed to do on account of that drop. It would have been of interest if the author could have included in the paper some information regarding the increase in capacity of the cable when the voltage regulator is in service.

## THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, LEEDS, AND MANCHESTER

**Mr. H. Diggle** (*in reply*): Mr. Johnstone Wright's figures show the economy which has been effected by the C.E.B. in standardizing on-load tap-changing directly on the h.v. windings of all their large transformers, and this is a policy with which I agree. It is of interest to note that the principal trouble has been in the overrunning of the gear. This, together with Mr. Longman's remarks at the Leeds discussion, supports my contention that a simple mechanical trip device such as that shown in Fig. 19 is necessary. I cannot agree with Mr. Sargeant that this warrants the description "complicated," and I disagree with his rather brutal method of a simple mechanical stop on the low-speed shaft, with reliance on a thermal overload relay to break the circuit to the motor after it has been stalled. A fairly high-speed motor, coupled through reduction gearing, necessarily subjects the gearing to considerable mechanical strains when the low-speed shaft hits a mechanical stop, and locks the gears up tight before the motor is stalled. The mechanism of Fig. 19 has the

same action as is performed by the driver of a motor-car who wishes to bring the vehicle to rest without mechanical shock, namely to disengage a friction clutch and then gently to brake the mechanism to bring it to rest. I am of the opinion that the difficulties of similar mechanisms, referred to by Mr. Sargeant, have been due to the use of a dog clutch instead of a friction clutch, and of operating it directly from a projection and lever on the low-speed shaft where only a very small angular travel can be made use of.

Mr. Johnstone Wright also mentions that the mid-point reactors with closed magnetic circuit have involved greater maintenance on the switches than those of the air-gap type, which rather supports my own preference for the air-gap type. Mr. Chadwick and Mr. Parry also raise this point and invite my views. If the closed magnetic circuit is used, the voltage-dips during a tap-change are likely to be greater for the same load on the transformer and will be greater than those shown in Fig. 10 for the air-gap type. The current to be broken when the reactor bridges two adjacent taps will be less for the closed-circuit type, but the back e.m.f. will be higher, so that the voltage at the switch contacts will be greater. When the load current passes in the transition position through half the reactor winding, a peaky voltage wave is formed with the closed-circuit type. Mr. Chadwick also raises the question of the effect of a short-circuit current when the tap-changer position is such that the load current passes through half the reactor winding. If the reactance of the transformer is such that the short-circuit current is 10 to 15 times normal there will probably not be much to choose between the two types, as they will both saturate magnetically at this current. On balance, the air-gap type seems to have the advantage, and appears to result in less wear of the switch contacts.

Mr. Chadwick and Mr. Parry advocate the general use of the mid-point of the reactor as a running tap. From the point of view of the designer of the transformer windings I agree that generally this is to be preferred, but the cost and losses of the reactor are then greater, as its physical size is increased and the voltage fluctuations during a tap-change are increased. In Fig. 10, if the mid-point is used as a running tap the voltage in every other position drops approximately 50 % below the value of a step, compared with only 25 % if it is not used with the bridging position as a running position. This point is generally not serious, however, and is chiefly of academic interest if the steps are reasonably small, e.g. not greater than $1\frac{1}{2}$ %. In practice, the question is generally settled by the number of steps required and by the number of available contacts on the tap selector switch. If the number of positions required exceeds the number of contacts, either the bridging arrangement [Fig. 9(*c*)] or the staggered tap scheme [Fig. 9(*d*)] can be used, but the latter is only advocated for cases where the power charges are such that the no-load loss must be the absolute minimum. Mr. Ellis and Mr. Parry refer to the use of an oiltight barrier between the transformer tank and the selector-switch chamber of a tap-changer of the types shown in Fig. 9(*c*) or Fig. 9(*d*). This is largely a matter of convenience in inspection. The barrier is not necessary from the point of view of operation of the switch, but generally this arrangement is to be preferred except where the number of taps is very large and/or very high-voltage tests have to be met. Although inspection of selector switches need only be infrequent, it is made more easy by the presence of a barrier, as shown in Fig. 15.

I cannot understand why Mr. Winfield suggests that I am not likely to agree with him that all switches, including selector switches, should be outside the transformer tank, as nearly all the examples which are illustrated exhibit this feature and it is my policy to adopt it, except for the limitations as to barriers given in the previous paragraph.

I do not agree with Mr. Winfield that integral construction of the tap-changer with the transformer tank is to be preferred to the bolted-on unit—particularly for large transformers. The advantages claimed by Mr. Sargeant for the removal of the individual units of a switch of the arrangement of Fig. 15(*b*) are rather hypothetical. From a manufacturing point of view the separate-unit system of Fig. 15(*a*) seems to have advantages, as transformers and switches are usually built by two distinct types of labour and it is preferable for each to complete his own job in his own department.

In reply to Mr. Sargeant's query, I cannot quote comparative data of life tests on the vertically moving oil-switch type of contact shown in Fig. 15(*a*), and the horizontally operating contactor type shown in Fig. 15(*b*), under exactly similar conditions. I have, however, used both types and have not found the latter to have special advantages. Mr. Mellonie in the Manchester discussion reports that no contact renewal has been necessary in 28 000 operations on the tap-changer of a 12 500-kVA transformer, using the vertical-break type shown in Fig. 15(*a*), so that this construction does not appear to have any special disadvantages in this respect; and, as is pointed out by two users' representatives—Mr. Longman and Mr. Bailey—it has positive advantages from the point of view of maintenance in enabling contacts to be quickly inspected without breaking oiltight joints or lowering oil. It is, of course, a construction which has been well tried out on oil circuit-breakers for many years.

Mr. Chadwick, Mr. Parry, Mr. Carr, and Mr. Mellonie, refer to the number of operations before current-breaking contacts should require attention. It is difficult to generalize on this point, as a particular design of switch may be used with different sizes of transformers where the kVA per step may be widely different, but probably the figure mentioned by Mr. Chadwick, namely 10 000, might be taken as a reasonable minimum to expect, unless the conditions are exceptionally onerous.

Mr. Winfield and Mr. Mellonie refer to the question of oiltight seals for shafts. Vertical shafts can be satisfactorily sealed by a method of balanced static pressures. Horizontal shafts are more difficult, but one patented construction, which appears to be satisfactory, employs spring pressure between a ground surface on a shoulder on the shaft and a ground annular ring which is enabled to seat itself by virtue of its attachment to a metallic bellows.

I agree with Mr. Winfield's opening remarks about the transfer of the generators to the primary network, and

that this is rendered possible by the development of on-load tap-changing on transformers. The slow practical development is perhaps surprising, but most new developments appear to have to wait several years for general application. Mr. Peck's summary of the early developments in this connection in America confirms that there is nothing fundamentally new in on-load tap-changing and that recent developments are only in the nature of the evolution of practical designs to meet present-day conditions.

I agree with Mr. Winfield that the prices of tap-changing gear for small transformers leave room for reduction, but improvements are being made steadily and purchasers can very much assist here by standardizing their requirements—particularly the maximum number of steps—and by restricting the requirements of the control gear. Frequently a number of transformers are specified to work in parallel and any increase beyond two in the number of equipments which have to be kept in step very much increases the cost of the control gear. If systems are properly designed it is difficult to see why each user need insist on his own ideas as to size of tap, number of taps, and maximum range of taps. Mr. Ellis points out that the C.E.B. standardized their requirements at the outset with mutual advantage to themselves and the manufacturer, and I welcome Mr. Carr's statement, as a user, that generally tappings need not be finer than $1\frac{1}{2}$ %.

Mr. Winfield and Mr. Siviour refer to the desirability of having a more quick-acting regulator to deal with the current-rushes due to starting-up motors on long straggling feeders which are normally lightly loaded. A solution does not seem likely through any form of voltage-controlled motor-operated regulator or tap-changer, as the rate of response is too slow. Series capacitors have been suggested but suffer from the objection that a fault on the line between the capacitors and the load subjects the capacitors to full line voltage and rather expensive protective arrangements are necessary. It is possible that in the future some form of electronic device will be used, and satisfactory arrangements can be rigged up in the laboratory to achieve the desired results. The short life of the filaments of present-day electronic devices, however, does not render them a practical proposition.

Mr. Winfield questions my statement that flywheel-type stored-energy devices are not suitable for hand operation, but I think it will be found that in the devices which are manufactured at present the motor and flywheel are uncoupled mechanically when the switch is operated by hand. Mr. Morris also mentions stored-energy devices and refers to the circuit of Fig. 9(*c*), in which separate transfer and selector switches are used. I agree that for this type the direct drive should be used and that the reactor should be continuously rated. In the paper I suggested the use of a direct drive of the type shown in Fig. 19 for this type of tap-changer. Stored-energy mechanisms are recommended primarily for the cases where preventive resistors are used. I agree with him that the speed of break is not of much practical importance on small loadings, but definite completion of a tap movement is important when separate transfer switches and continuously-rated reactors are not used.

I do not think there is much practical significance in Mr. Morris's point that the selector switches in some cases are in compartments at a level with the hottest part of the oil in the transformer tank. The temperature in the switch tank is lower than that of the transformer tank; mechanical distortion is unlikely, and can be overcome by the use of flexible couplings, etc. Any possible risk of loss of alignment of contacts can be overcome by designing them to be self-aligning.

Mr. Ellis, in the Manchester discussion, refers to the limits of application of stored-energy devices. Spring-loaded and falling-weight schemes are not, I believe, generally used on transformers above about 4 000 kVA. In the falling-weight design, stored energy can be used only in one-half of a revolution of the operating shaft. This also applies to some forms of spring drive, so that they are both generally only used on circuits which do not have separate transfer switches. There is no such inherent limit to the flywheel scheme, and it is used by some makers on the largest types where separate selector and transfer switches are employed.

Mr. Winfield appears to have read into my remarks under Section (5)—referring to impulse testing—a suggestion as to the inadequacy of B.S.S. No. 171—1936, which deals with power transformers. Impulse testing is not dealt with in the present Specification, and my object was only to draw attention to the effects of impulse-voltage testing on the insulation requirements of the tap-changing switch. As Mr. Ellis pointed out in the Manchester discussion, the question of standardization of impulse-testing values for transformers is at present under consideration, and in due course the tap-changers will have to be subjected to impulse tests when coupled to the transformer, if and when this condition is specified.

Mr. Parry and Mr. Pattinson refer to the number of turns of the hand crank of a motor-operated tap-changer, and advocate one turn only per tap-change, e.g. by putting the crank directly on the shaft O of Fig. 19. In principle I agree with this for small tap-changers, but the effort required to turn a large tap-changer precludes this, and gearing must be introduced. The gear ratio should be the minimum consistent with reasonable physical effort, and the number of turns does not exceed 10 in the design shown in Fig. 19.

In reply to Mr. Chadwick, I have no preference for the scheme of Fig. 9(*b*) and only use it for small equipments such as the mercury-switch scheme of Fig. 18. On short-circuits, the reactor will saturate. Insulation difficulties are not likely to arise, particularly if the scheme is used only in relatively low-voltage circuits.

Mr. Chadwick invites discrimination between the schemes of Fig. 9 and Fig. 11. The parallel-winding scheme [Fig. 9(*a*)] is not advocated, for the reasons given in the paper, and that of Fig. 9(*b*) is only suggested for small equipments. Generally the scheme of Fig. 9(*c*) is to be preferred for large transformers. Principally for reasons of cost, the resistor scheme of Fig. 11(*a*) is recommended for small equipments. On the Continent, the resistor scheme of Fig. 11(*c*) is extensively used on large transformers. Provided a well-designed stored-energy mechanism is used to prevent the resistor being accidentally left in circuit, there seems no valid objection

to the scheme beyond the fact that it requires one tapper voltage position; and, as pointed out by Mr. Peck, it would appear to have an increasing application. As suggested by Mr. Ellis in the Manchester discussion, however, it is necessary for a purchaser to accept a short-time-rated resistor, and the figures given by Mr. Hinings clearly show that continuously-rated resistors for large equipments have losses of such a value that adequate cooling facilities for continuous rating are impracticable.

Mr. Pattinson and Mr. Sargeant disagree with my recommendation not to insert the limit switches directly in the motor circuit. In reply to Mr. Pattinson, I prefer to avoid the use of contactors with throw-off devices and consider that a positive mechanical declutching device (e.g. Fig. 19) which is independent of any electrical considerations is likely to be more satisfactory. I agree with Mr. Sargeant that there are many industrial applications where limit switches provide an adequate safeguard, but usually the angular margin in which the mechanism must be stopped is not as critical as that in a tap-changer drive, as shown in Fig. 20. It is a statement of fact that the timing is more critical if the limit switches are in the motor circuit. Contact 55 and the limit switches in the end positions must then either open together, or the limit switch very slightly after contact 55. As these are on different shafts with an intermediate gear ratio of perhaps 15 : 1, the timing of the limit switch's opening is obviously more critical than when it is permitted to open at any time during the complete revolution of the last tap-change, as in the case when the limit switch is put in the contactor-coil circuit. As stated in the paper, my preference is for positive mechanical rather than electrical means to guard against a contactor sticking in. Regarding the wrong connection of limit switches, I have experience of a case where, owing to a change in the wiring at the point of supply, the phase rotation of the motor was reversed and the limit switches rendered inoperative, so that the only positive safeguard was a mechanical device.

In reply to Mr. Patmore, there are quite a number of cases of tap-changers installed in the premises of industrial consumers, and of current-operated boosters in those of domestic consumers. The small Hungarian regulator which I mentioned in reading the résumé of the paper is intended to be put in each flat of large apartment buildings.

Mr. Ryder, Mr. Parry, and Mr. Carr, refer to the effect of the adjustment of the time-delay setting of the relay on the number of operations of automatically-controlled equipments. The figures quoted in Tables A and B, which are taken from reference (14) of the Bibliography, show the advantages in a particular case of having a reasonably long time setting and also of not having the sensitivity of the voltage-regulating relay less than the value of one tapping step. My own recommendation is that the sensitivity of the voltage relay should be about 1·25 times the mean tapping value, and generally the American figures quoted in Tables A and B line up with my own experience. The only cases where I can see that short time settings are necessary are in cases similar, I believe, to that quoted by Mr. Carr, where the load builds up suddenly and falls off suddenly at definite periods such as the starting-up and closing-down periods of the load of a large factory. In one case of which I have knowledge the incidence of the load causes a voltage-drop to correct which 7 tap-changes are required, and unless the time setting is reasonably small an excessively long period will be required to drop the voltage by 7 taps when the load falls off again at midday and evening. In such a case 28 operations per day appear to be inevitable, apart from any required to compensate for voltage fluctuations.

Mr. Pattinson suggests that, on a failure of the supply to the voltage-relay coil, the tap-changer should run automatically to the mid-voltage position instead of to the lowest-voltage position. This could be arranged, but only by the introduction of further contacts. With regard to "freezing" of the contacts of voltage-regulating relays, high shunting resistances appear to have eliminated this class of trouble, particularly when silver contacts are used, and I confirm that this seems to be the most suitable material. Provided the loading of the circuit which is "made" and "broken" by the relay is reasonable, there is no trouble with open contacts in modern relays, and any freezing troubles, in my experience, have been due primarily to the nature of the circuit and not to the relay itself. It is too early to comment on the new "Astatic" relay, which uses mercury switches, but, as pointed out by other speakers, mercury switches may be a source of trouble unless carefully selected and rated. With regard to radio interference due to the relay contacts, there appear to have been very few cases of complaints and there does not seem to be justification for the general inclusion of interference-suppressors. With regard to the adjustment of the balance point of voltage-regulating relays, most modern relays include an adjustable rheostat in series with the coil. A graduated scale is now included by some manufacturers, but it is doubtful whether it is necessary to calibrate this in volts. I cannot offer any simple solution of the problem of checking the intermittent failure of automatic gear to function, which is sometimes reported. Many complaints of periods of low voltage are difficult to substantiate by reliable evidence, and doubt is sometimes cast on their genuineness.

Mr. Pattinson and Mr. England refer to the two-step current-operated booster, one of whose advantages, namely no "no load" loss at light loads, I omitted to mention in the paper. The regulator mentioned by Mr. Pattinson (British Patent Specification No. 433904) has, I believe, not yet been developed in a practical form.

Mr. Ryder, in the Manchester discussion, points out that Mr. Norris's comparison of the apparent complication of the automatic control circuit of Fig. 22(c) with that of his Fig. A, which shows the simplest arrangement, in which the relay contacts are connected directly to the motor on the tap-changing mechanism, is not very useful unless the operating characteristics are reduced to a common basis and the apparatus has to perform similar functions. Even if the criticism of the complication of the control circuit were justified, it would appear to have no bearing on the desirability of accessibility of the parts of the tap-changer itself, for which a plea was made in the paper. The control circuit of Fig. 22(c) admits of

no essential simplification if proper step-by-step action of the tap-changer has to be achieved and adjustment of the time-delay period is also required. The simple circuit quoted by Mr. Norris is in use by several manufacturers for small independently-operated equipments which are not intended to be operated in parallel and where a fixed time-delay is permitted by gearing in the mechanism. The induction disc type of motor can only be used for small units. On large units, e.g. those for which Mr. Norris advocates the parallel-winding system, conventional types of motor, such as that shown in Fig. 22(*c*), must be used. Further, if parallel control of two or more equipments is envisaged the circuit will bear no resemblance to the simple one shown in Fig. A.

A number of speakers refer to the use of mercury switches, and I agree with Mr. Norris and Mr. Southorn that, provided they are suitably rated and selected, there is no reason why they should not be used. I agree with Mr. Pattinson that follow-up cams should be used to ensure positive opening of the switches, and this requirement is met by the construction shown in Fig. 18. Mr. England's remarks in connection with the ease with which on-load gear can be added to existing transformers refer, I believe, to the addition of a mercury-switch-type tap-changer above the transformer yoke. Even in this case the existing tappings will usually have be to rearranged. For anything larger than a distribution transformer, I think that my statement is correct that it is not generally possible to add tap-changing gear to an existing transformer without considerable expense, and this appears to be confirmed by Mr. Longman's remarks.

Despite Mr. Norris's spirited defence of the parallel-winding scheme, the fundamental fact remains that the windings are overloaded by 100 % during a tap-change, with consequent danger if the gear fails to complete an operation, and risk of interruption of the main supply. I assume that, in computing that the risk of an incomplete tap-change is only once in 864 years, Mr. Porter has had in mind the probability of the failure of the supply voltage to the control circuit coinciding with the period of a tap-change. The principal trouble is not due to failure of the supply to the control circuit but to failure of the supply to the motor itself owing to a dirty contact, the blowing of a fuse, or tripping of an overload relay, etc. It cannot be assumed that auxiliary contacts will never fail to make or a fuse to blow, and, owing to an unlubricated bearing or other cause, the motor may become overloaded and the thermal overload relay trip during a tap-change. Mr. Smith reports a case of the latter type, and I have had experience of fuses blowing. These can hardly be considered exceptional causes, and the 864-years argument does not appear to apply. The fact that equipments have been operated for a period without disaster does not necessarily prove that their principles are sound, and it is significant that the American firm which originated the parallel-winding scheme has abandoned it—primarily, I believe, owing to the objections of customers to the fact that the main supply must be interrupted if the gear fails to complete an operation. I cannot agree that the possible calamities to the switch mechanisms, mentioned by Mr. Norris in his remarks at the Manchester discussion, are at all likely in gear made by reputable manufacturers. The switch mechanisms of the parallel-winding and reactor schemes of Figs. 9(*a*) and 9(*c*) are essentially the same, so that the latter has no greater possibilities of failures of this nature. There appears to be considerable exaggeration in the implication that the failure of the supply to the motor is a more remote contingency than a serious mechanical failure in the switch mechanism. The location of the tappings on the inner or outer windings is generally determined to a large extent by the voltage of the winding on which they are specified. The tests which are reported in the last paragraph of Mr. Norris's remarks cannot overcome the fundamental objection that the windings are subjected to an overload of current of 100 % during a tap-change.

Mr. Atkins appears to be in error in stating that transitorily the effective impedance of the transformer may be doubled during a tap-change, when half the reactor winding is in series with the main windings. This does not apply to the air-gap type of reactor, as is shown in Fig. 10. The value of the added reactance is approximately equal to one-half of the percentage value of one tapping section, e.g. of A–B in Fig. 10. As the latter may be of the order of $1\frac{1}{2}$–3 %, depending on whether the mid-point of the reactor is used as a running tap or not, and as the reactance of a large transformer may be 10 %, the momentary increase is only relatively small, e.g. from 10 % to $11\frac{1}{2}$ %. The alleged wide voltage-swings during a tap-change when reactors are used does not apply with the air-gap type, as is shown in Fig. 10.

Mr. Southorn recommends independent regulators on each phase of the l.v. side of a 3-phase transformer. There is no objection to this provided the purchaser is prepared to pay for it, but it is not generally justified, and a single tap-changer on the h.v. side is usually all that is required. I cannot agree that there is any practical advantage in a booster scheme, such as Fig. 2, compared with a simple tapped auto-transformer, from the point of view of protection against short-circuits. Both have very low effective reactance and require some form of series impedance (e.g. a double-wound step-down transformer) to make them able to withstand short-circuits across their terminals. I agree that it will be an advantage when a standard description is accepted for the current-breaking switches, which I refer to as "transfer switches." The purpose of the small magnets and the iron disc at the top of the relay in Fig. 23 is to give only three stable operating positions of the contacts —floating, or made at either the top or the bottom contact—and thus prevent chattering at the contacts.

I agree with Mr. Smith that a triple-pole protective relay should be used for 3-phase motors. This agrees with my standard practice, although only two poles are shown in the diagrams of Fig. 22. In reply to Mr. Hedley, I cannot see any fundamental advantage for a selector switch of the type which bridges a pair of tapping contacts compared with one which carries current from one contact only to a centre point, and the former type appears to have application only in the parallel-winding system of tap-changing. The maximum current which is handled without transfer switches does not usually exceed about 100 amperes.

I agree with the opening paragraph of Mr. Carr's

remarks on the application of regulators, and Mr. Ryder has dealt partly with the question of reducing the burden imposed by the voltage relay on the potential transformer.

I have no direct experience of the tuned-circuit types of relay, but it would appear that these must be affected by variations of frequency. This is, however, not of much practical significance on modern systems.

I agree with Mr. Mellonie's two recommendations, although the second one is not always easy to achieve,

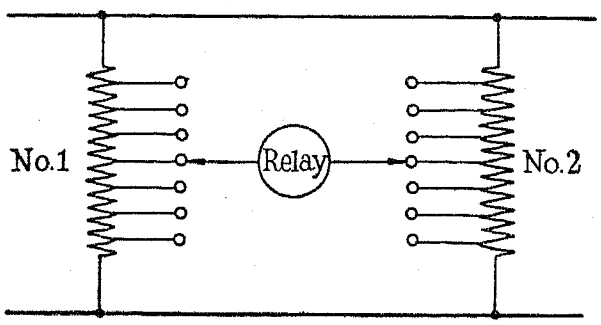


**Fig. B.**—Potentiometer resistances for parallel control of two equipments.

and I am obliged for his figures as to records of operating experience. Mr. Mellonie advocates operating transformers in parallel. For the reasons given in the paper this is not the view held by all operating engineers, but the operation of tap-changers in parallel does not present any fundamental difficulties, provided the number of units is not excessive.

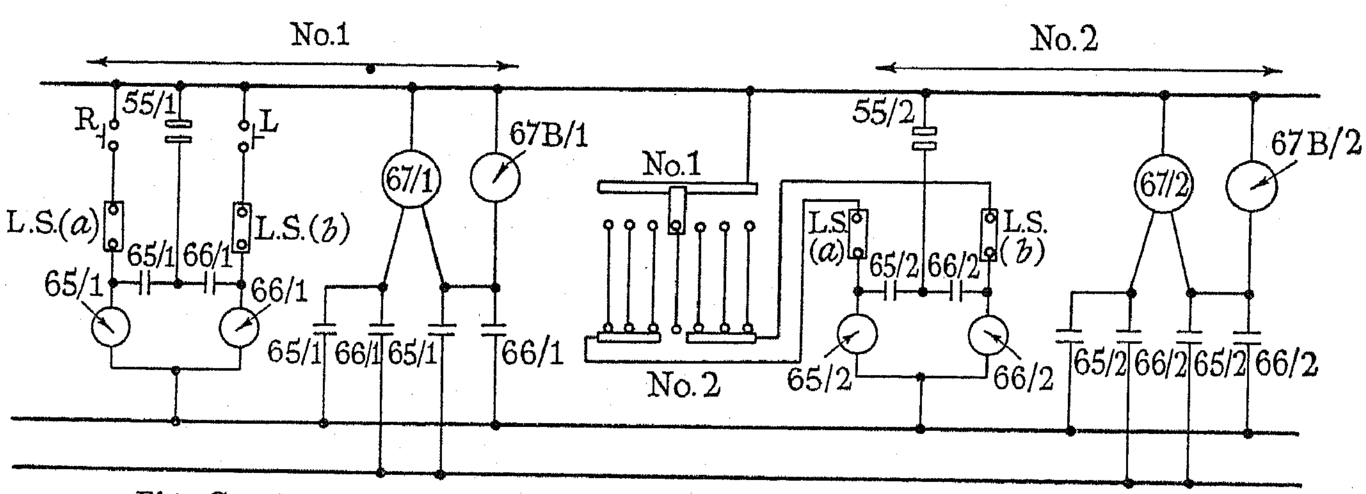


**Fig. C.**—Parallel control of two equipments by "follower and leader" method. (For symbols see Fig. 22.)

Mr. Goodman, Mr. Parry, and Mr. Ryder, request particulars of methods of parallel control. This subject would require considerable space to deal with fully, and only the essential principles are dealt with below. Broadly, parallel-control arrangements are based on two methods: (*a*) simultaneous operation of the motor contactors of two or more equipments, with protective devices which lock out the control circuit if one equipment comes to rest in a position differing by one tap from that of the other or others; and (*b*) "follower and leader" schemes in which one equipment only is moved by the operation of the control switch. When the first one has completed a tap-change it automatically energizes the circuit of the contactor of the following equipment, so that the latter then also completes a tap-change. The principles of simultaneous parallel control can be achieved in one way by extending the circuit shown in Fig. 22(*b*), so that two or more multi-contact switches and potentiometer resistances are connected to the one handwheel and thus operate the control circuits of the several equipments simultaneously to move the same number of taps. A frequent method of protection against equipments falling out of step is to connect a relay between the potentiometer resistances and the tap-changer mechanisms, as shown in Fig. B, so that the relay becomes energized if they remain on different positions and its contacts are connected so as to prevent further operation and possibly to operate an alarm.

A variety of "follower and leader" circuits are used by various manufacturers, but the one shown in Fig. C (British Patent No. 364821) achieves the result without the use of any additional relays. This diagram has been drawn as an extension of Fig. 22(*a*) and, for convenience, the thermal-overload relay connections have been omitted. No. 1 equipment is controlled exactly as described in the paper for Fig. 22(*a*). A multi-contact switch, in which the arm makes contact with only one fixed contact at a time, is fitted to the tap-changer mechanism of No. 1 equipment, and a special multi-contact switch to that of No. 2. The latter switch connects the fixed contacts into two separate groups, with one left unconnected. Connections from the two groups are taken to the contactors of No. 2 equipment and the corresponding fixed contacts of the two switches are joined together. In the position shown, both mechanisms are in the same positions and there is no circuit between the multi-contact switches. If No. 1 equipment moves one tap, the arm of its multi-contact switch will connect to the next fixed contact to the left or the right. A circuit is then completed through the switch on No. 2 to energize either contactor coil 65/2 or contactor coil 66/2, which then runs its mechanism in the same direction until balance is restored in the auxiliary circuit. The scheme can be similarly applied to automatic control. The extension of any system of parallel control to more than two equipments adds considerably to the complication of the circuit and to the cost—particularly if selection of the leader is required—and should be avoided wherever possible.

In reply to Mr. Needham's query as to the economical advantages of applying a voltage regulator to a particular size of cable, I would refer him to reference (14) of the Bibliography.

# THE EVOLUTION OF THE MINERS' ELECTRIC HAND-LAMP*

By WILLIAM MAURICE, Member.

(*Paper first received* 18*th November*, 1936, *and in final form* 26*th January*, 1937.)

## SUMMARY

The paper opens with a discussion of the causes leading up to the general adoption of electric mine lamps, and an account is given of the awards in the Home Office prize competition of 1911. The evolution of the alkaline mine-lamp accumulator is next considered, and the principles of construction of Edison, Jungner, and Wolf accumulator plates are described. The stages are traced in the development of the Wolf alkaline lamp from 1912 to 1919, and the successive changes in the design of filling-hole stoppers and tools for handling, automatic devices for electrolyte level testing and filling, and prevention of alkali leakage, are discussed. The evolution of the two-part lamp is next considered, and improvements in contact plates, locks, locking systems, bulbs, and cover glasses, are examined. Comparative polar curves and Russell diagrams are given showing the advances in lighting values, and illustrations of typical "Schedule A" type electric hand-lamps are included. Reference is made to the present position regarding electric mine lamps with fire-damp indicators. The final section of the paper deals with the new statutory mine lighting regulations.

## INTRODUCTION

The general adoption of the portable electric mine lamp dates from, and was in large measure a direct result of, the passing of the Coal Mines Act, 1911. One of the practical consequences of that important revision of mining legislation was to render obsolete great numbers of flame safety lamps of low grade and thus create a large market for new lamps. The collieries had to acquire new lamps, and the opportunity was open to them either of getting better flame safety lamps or of using electric lamps. The miners' electric lamp was, however, only just developing in 1911, and it could not be said that there was any well-established type either at home or abroad.

There was, in fact, virtually only one lamp in Great Britain. It was known as the Sussmann lamp. It was, originally, a 4-volt lamp with flat-grid pasted-lead accumulators and a semi-solid sulphuric-acid electrolyte. The battery consisted of two rectangular ebonite cells each containing one positive and two negative elements. The cells were assembled in a flat-sided iron box with hinged lid, on the top of which a bulb was mounted between conical reflectors and enclosed in a glass cylinder such as those which were used in flame safety lamps. The complete lamp weighed about 3½ lb. and was said to have a capacity of 5½ ampere-hours. The 2-cell arrangement did not prove a success, and the lamp was changed to a single-cell 2-volt model. It was in use at Murton Collieries, Co. Durham, from 1897 onwards. The lamp was later improved by Mr. W. E. Gray, and was known for many years as the "Gray Sussmann." The "Gray" lamp of to-day is in the direct line of succession. Murton still uses the same type and is probably the only colliery in the world which has used electric hand-lamps continuously for 40 years.

Nevertheless, the general feeling in 1911 was that there was no lamp available of such outstanding merit as to justify its wholesale adoption by collieries. Something had to be done to stimulate the lamp makers and inventors. A well-known colliery owner rose to the occasion by placing a sum of £1 000 at the disposal of the Home Secretary, to be awarded as a prize for the best electric lamp for use in coal mines. A competition was announced which was to be open for 6 months and closed at the end of 1911. The awards were issued in August, 1912: 195 lamps were submitted, but none was held to be good enough to receive the whole prize. It was accordingly split into one of £600 and eight of £50 each. Of these eight lamps, four never came into general use, three others were only used on a comparatively small scale, while one, the Oldham, eventually went far towards outrivalling the "prize" lamp in popularity. The major award went to a lamp designed by Mr. Faerber, of the Concordia Elektrizitats A.G., Dortmund. This lamp, which afterwards became known as the "CEAG," was originally a 2-volt free-acid lamp with cylindrical positive and negative plates assembled concentrically in a celluloid case. There seems to be some uncertainty as to where the idea of making cylindrical battery plates originated, for about the time that the C.E.A.G. concern produced the cylindrical form rolled up from flat plates the mould for direct casting of such grids was invented and used by several Continental lamp-makers. The use of concentric cylindrical elements became standard practice with several firms, and remained until the 2-volt lamp became obsolete.

Other novelties in the "prize" lamp included loose spring plunger terminals designed with plug extensions which dropped into sockets in the battery lugs so that they could quickly be taken off for cleaning. The battery was held in a container of tinned sheet steel rolled into a cylinder, with horizontal corrugations for resistance to mechanical impact. A crude form of bayonet joint was riveted to the top of the case to form the means of attaching the lamp top. This was of the 4-pillar type and carried a contact plate, lampholder, bulb, and flanged dome-shaped protecting glass. The bulb had a conical cap without the usual bayonet-joint pins, and it dropped into a lampholder of the same shape. It was held against the lampholder contacts by a spring which rested between the roof of the cover glass

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and the top of the bulb. The idea was to provide a means of breaking the circuit in the lampholder in the event of the glass being broken. This constituted the essential patent in the lamp.

The donor of the prize money having given this new lamp a remarkable start by buying 10 000 lamps for his own collieries, it obtained worldwide publicity and at once became an established type. Thus was started a boom in electric mine lamps and, whether for good or ill, the 2-volt lead-acid lamp became substantially the only type used in Great Britain for the next 20 years.

The Oldham contribution to electric mine-lamp design did not at once emerge in the form by which it has so long been known. Originally, it had a cylindrical aluminium case about 2½ in. diameter, and was provided with a cylindrical form of accumulator. It was soon superseded by two other models having rectangular cases, and lamp tops hinged to the container. Then came a series of models embodying the well-known characteristic of the Oldham lamp, which is the arrangement whereby the lamp top and container are made in one piece, the battery being inserted from below and secured by means of a cast brass screw-on base. It is open to question whether the acceptance of the 2-volt lamp was not rather too hurried, for, as subsequent events proved, very few of the conditions laid down by the prize adjudicators, excepting cheapness, were adequately fulfilled. In particular, the specified lighting value of "not less than 2 candle-power continuously for 10 hours" never came near achievement. Minor improvements in 2-volt lamps came by degrees, partly as a result of increased experience and partly through Mines Department Orders requiring defects to be remedied which had caused dangerous conditions to arise.

## ALKALINE BATTERIES

Even before the Prize Committee got to work a new movement had been developing which was destined to change the type and style of miners' electric hand-lamps throughout the world. Experiments had been made in Germany with "alkaline lamps," containing a new kind of storage battery, and two or three mines had been equipped with them. The early trials were all failures, but this type of lamp eventually dominated most of the coal-mining areas of the world. It is in one of these lamps that nearly all the vital improvements in electric mine-lamp design have been made.

The alkaline accumulator or storage battery is commonly associated with the name of Thomas Alva Edison. Earlier than 1912 there was no such expression as "alkaline battery" in use. "Edison battery" was originally the only name by which accumulators with an alkaline electrolyte were generally known. A Swedish scientist, Dr. Jungner, was also studying the possibilities of this new type of accumulator, and he and Edison ought to be bracketed as the joint inventors of the principle of the alkaline accumulator. Jungner evolved the first nickel-cadmium accumulator, and took out British patents for it in 1900. Edison evolved the first nickel-oxide-iron cells, which obtained British patents in 1901. There are still only these two basic types of alkaline mine-lamp accumulator, the Edison and the Jungner, in general commercial use. The Edison is known as the nickel-iron type of accumulator because nickel hydroxide is used as the active material in the positive plates and reduced iron is used for the active material in the negative plates. The Jungner accumulator was the first nickel-cadmium combination, having nickel hydroxide for positive active material and cadmium oxide for negative active material.

The respective types are thus characterized as nickel-iron and nickel-cadmium accumulators. Both are successful and are in extensive use for many purposes. Each type has some advantages of its own for certain applications, but for mine lamps the nickel-cadmium type has proved to be by far the better. There are now many variants of the nickel-cadmium type, and it is first necessary to ascertain the difference between one and another and determine the extent to which these differences may affect results. There are two fundamental differences to be examined first: one lies in the nature of the active material used, the other in the means whereby the active material is made into battery plates or electrodes.

The substances taking part in an electrically reversible chemical reaction are, when in a condition to furnish electricity, known as the "active materials." For efficient working the whole of the active material should take part in the reaction, and to approach this condition it is necessary in practice to employ the active materials in a state of fine division, or powder. The initial problem, therefore, is to find out how to make these powders perform their electrochemical functions in the most practically efficient way. Means have to be devised whereby these powders can be held together in suitable form. The mechanical devices whereby this end is achieved form the "supporting medium." Devising a satisfactory supporting medium would present no serious difficulty if the active materials were electrically conductive. Since usually they have such a high resistance as to be by comparison non-conductive, a new problem is introduced which presents many difficulties.

Because, substantially, all the electrochemical changes take place in the active materials, and none in the supporting medium, it follows that the efficiency of the battery depends on the extent to which the active materials are enabled to participate. If, for example, all the positive active material were dropped into a perforated iron box, and all the negative active material were dropped into another perforated iron box, and the combination were put into electrolyte and treated as a battery, the results would be insignificant because there would be practically no chemical activity between the particles owing to the lack of electrical conductance. Only those tiny portions of the active material in contact with the walls of the box would function. Reaction would not spread throughout the mass. Edison's method of supporting active material is to take steel ribbon minutely perforated (to allow free circulation of electrolyte in the active material), nickel-plate it, and then fold it into small pockets of rectangular section, with one end left open for reception of active material. The pockets are filled with active material, tamped by special loading machines, the ends closed, and the finished elements assembled in nickeled-steel frames to form plates or electrodes of standardized dimensions.

Manufacturing difficulties are as often due to the means of retaining and supporting the active materials as to these materials themselves. It is thus evident that the theoretically perfect combination of active materials may fail in practice because the means of support fail to provide for electrical conductance throughout the mass. In the original Edison positive plates it was found that the nickel hydroxide swelled and caused the pockets to burst. Earlier than this it had been realized that it was necessary to mix something with the active materials to make them conductive. In Edison-type cells, flake graphite or nickel flake was added to the positive active material. When the early flat-plate Edison positives gave trouble owing to the active material swelling and bursting its supporting medium, and the plates lost capacity on account of difficulties with the graphite filling, Edison set to work to evolve an entirely new form of supporting medium.

His new idea, developed mainly between 1906 and 1908, was to put the active material into tubes instead of rectangular pockets, and so to construct these tubes that they would offer sufficient mechanical resistance to internal pressure and resulting tendency towards distortion. In order to bring about this result he took the same narrow perforated strip as was used to make the pockets and twisted it spirally, as in making a paper spill. These spiral tubes were held together by steel rings, suitably spaced, and the tubes, when filled and closed, were assembled in a frame to form a plate, alternating tubes being laid the reverse lay of the spiral in order still further to resist the tendency towards distortion. This construction (shown progressively in Fig. 1) is known as the "Edison tubular positive." Sets of finished positives and negatives appear as in Fig. 2, the positive group being shown on the right. The invention of the flat-plate type of supporting medium and of the machinery for its commercial production seems also to have been essentially the work of the Edison laboratories and, with one exception, much the same mechanical construction is used in all alkaline accumulators to-day.

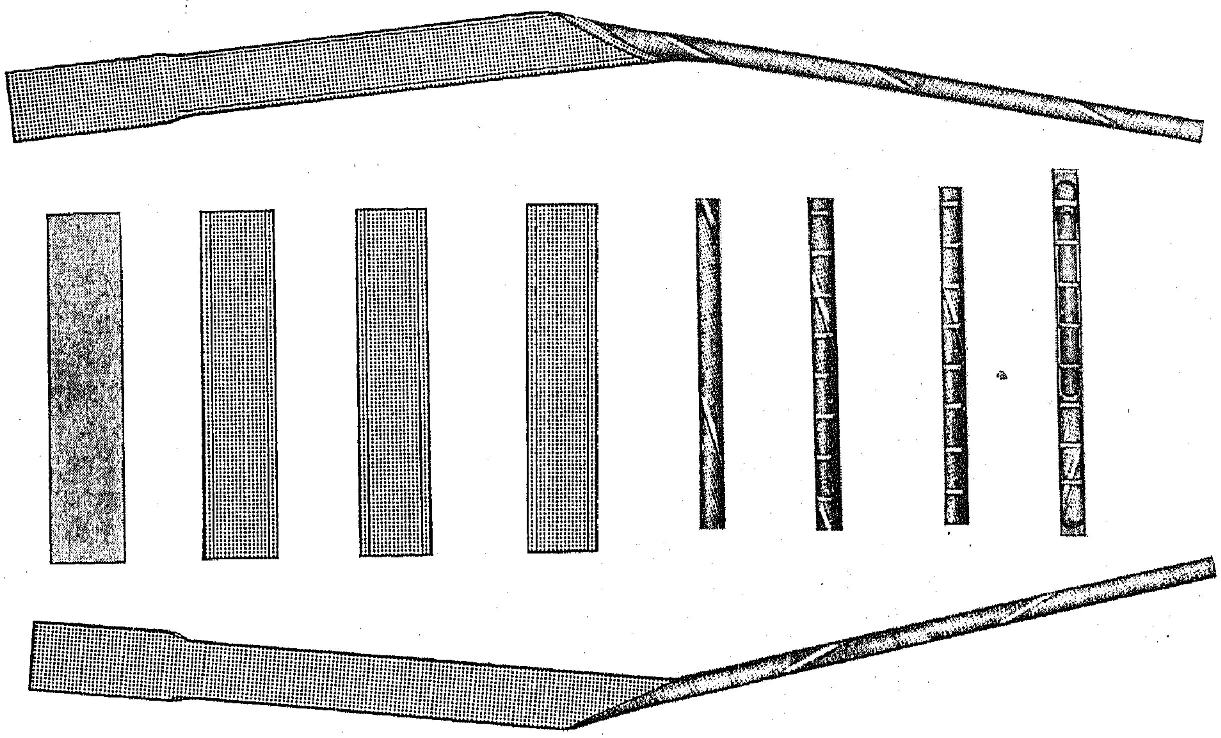

Fig. 1

In Jungner (nickel-cadmium) type cells the same problem of how to make the active materials conductive had to be worked out, because substantially the same mechanical form of supporting medium was used. In the case of the positives a graphite conductor was usually added. The Jungner negative did not present such difficulty as had been experienced with Edison negatives, because cadmium oxide has a much lower electrical resistance. In use, however, it has a tendency to cake and lose porosity, and is therefore generally mixed with a small quantity of iron. The advantage of adding iron to the cadmium oxide was the outcome of extensive research conducted by Jungner, and ranks as one of his important discoveries.

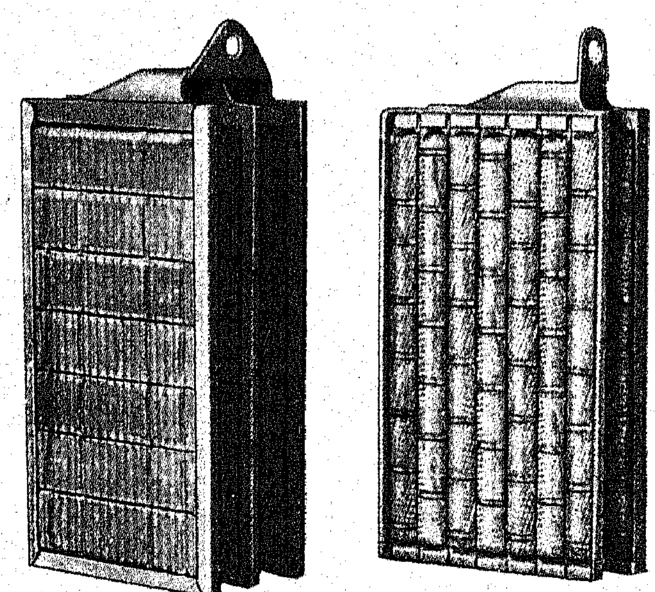

Fig. 2

The results obtainable from any given plate construction are determined not only by the chemical but even to a greater extent by the physical condition and structure of the active material, the latter varying according to the particular process under which it is made. Thus far we have seen that the active materials are held in a supporting medium which is fundamentally

a series of boxes, and extraneous matter is added to make the mass conductive. In 1909, another inventor, named Porschke, suggested a supporting medium for the active materials which would overcome all the difficulties associated with the earlier form of alkaline accumulator. Porschke reflected that the first cause of the trouble was the swelling of the active material, and consequent necessity for providing a supporting medium designed to resist stresses. Reasoning further, he saw that the addition of conducting elements to the active material, hitherto enforced by its non-conductive properties, was a necessity to be circumvented if possible. It was clear that the elements which had to be put into the active material to make it conductive constituted only a mechanical mixture, and a mechanical mixture did not necessarily guarantee completely intimate contact with every particle of active material. Graphite, moreover, had a tendency to wash out. He therefore considered whether it was not possible to devise a framework for the support of the active material which would allow it to "breathe"—to expand and contract with the alternating changes of volume of each charge and discharge—without setting up structural strains. If, he surmised, he could do this, and at the same time avoid the necessity for adding conductive material, he would expect to produce an alkaline accumulator possessing advantages not previously obtained. Porschke's basic idea was to make a metallic net which would expand and contract without distortion, make the interstices as fine and as close together as was possible, turn the active material into a paste, and paste it into these minute interstices. In the first trials a woven nickel gauze was used, and the nickel hydroxide was made into a paste and pressed into the meshes of the gauze. In subsequent experiments a nickel gauze was made, so fine that the interstices were almost invisible to the naked eye, and, as every minute hole received its fullest quota of nickel hydroxide, practically all of which was in contact with the nickel wire, the basic idea was well on the way to being realized. Originally, the pasted woven gauze strips were rolled up, pressed, and used as single electrodes. Later experience showed that finely perforated nickel foil lent itself better to the manufacture of mechanically strong electrodes. Several years were spent in developing this radically new way of making an alkaline accumulator and in devising machinery for its manufacture. By 1912 it had assumed the form in which it appears to-day, apart from improvements in methods and processes, which are continual.

The procedure is to take pure nickel foil or ribbon, Fig. 3 (left to right), and pass it through a perforating machine which pricks minute holes all over it. The holes, being pricked, instead of punched, have a rough side and a smooth one. The rough side is pasted with a prescribed weight of nickelous hydroxide and then doubled so that the two rough sides are in contact with each other and the microscopic projections around each hole key into each other and touch every particle of paste. The doubled strip is next passed through another machine which folds it zigzag, as shown. It is then compressed to form what is technically known as a "cake," and these cakes are mounted in pure nickel frames to form the finished electrode. The way in which Porschke's original ideas were worked out in practice will now be seen from the construction of the electrodes. The paste is so perfectly keyed into the structure that every particle becomes conductive. The paste is inside the nickel foil and cannot wash out, and the "concertina" action of the folds during charge and discharge allows for changes of volume without throwing any strain on the structure. All these developments had been made by the parent Wolf firm, who had acquired the manufacturing rights in the Porschke invention. Thus it became known as the Wolf alkaline accumulator.

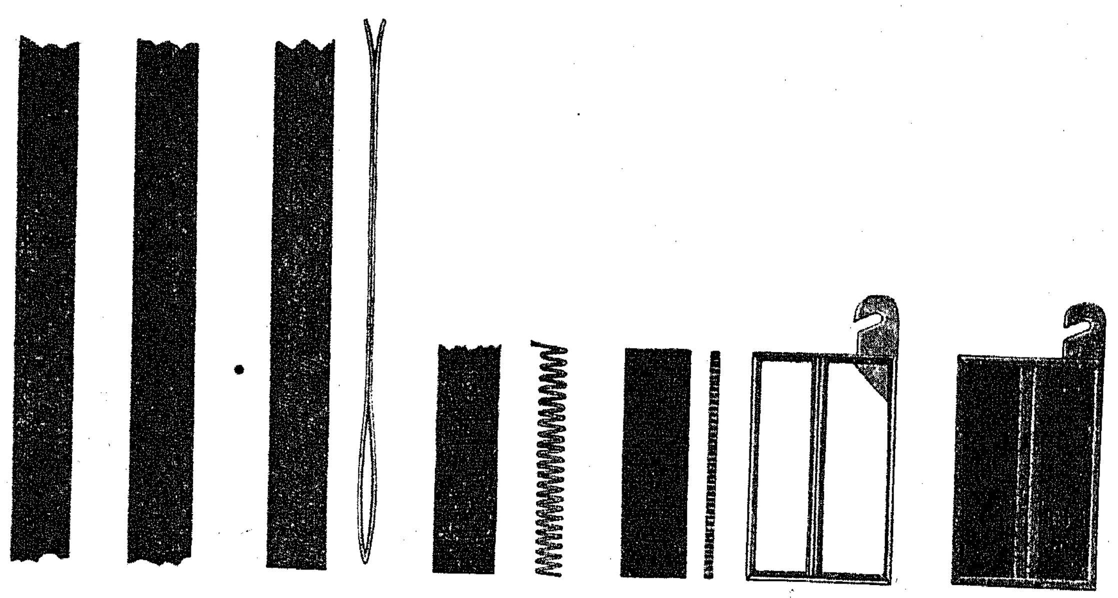

Fig. 3

It had already been shown that all alkaline accumulators suitable for use in mine lamps are either nickel-iron or nickel-cadmium combinations. During recent years there has developed a tendency to mix the types, retaining Edison constructional forms while employing Jungner active materials. It has also been shown that (apart from minor variations) alkaline accumulators are made in three different mechanical forms, namely (1) the original Edison construction, in which the active materials are filled into small rectangular steel pockets; (2) the combination of form (1) negative plates with the tubular steel positives constituting the Edison development of

1908; and (3) the Wolf construction (dating in practice from 1912), in which the active materials are applied to perforated and folded pure nickel foil.

Forms (1) and (2) require the addition to the positive active materials of graphite or nickel flakes in order to make them conductive. Form (3)—the Wolf construction—employs no added conductors and no steel pockets, and requires no special means of preventing distortion.

## EVOLUTION OF THE ALKALINE LAMP

We have now reviewed all the alkaline-battery systems so far as they have been applied to mine lamps. It remains to be seen how the first successful miners' alkaline hand-lamp was evolved. Every first-class mine lamp has been developed by the tedious process of trial and error, until, eventually, all the unlooked-for troubles have been eliminated. It is comparatively easy to design a satisfactory electric mine lamp when there is prior experience upon which to draw. It was a long and very costly business to develop a new accumulator construction straight from the raw materials, when even the machinery for achieving the desired ends had first to be invented. The production of a new lamp was little less difficult, because in 1912 the design of even lead-acid lamps was largely experimental and no earlier lamp with an alkaline accumulator had ever been satisfactory.

### Early Types

The first successful miners' hand-lamp with an alkaline accumulator was that introduced in 1912 and designated the "Wolf alkaline lamp." This was the origin of the expression "alkaline lamp," which has since become a generic term for all lamps with alkaline accumulators. The Wolf alkaline lamp was the first miners' alkaline hand-lamp to come on the market and stay there. Apart from a few sporadic competitive efforts which contributed nothing towards establishing essential principles of design, the Wolf alkaline lamp stood alone for 15 years, becoming the most widely used lamp on the Continent while it was being comparatively neglected in Great Britain. In its gradual evolution one problem after another was faced and solved. The 1912 Wolf alkaline lamp seems to have been the first electric mine lamp for which a cylindrical battery case was made of steel drawn and pressed from the sheet. It was an original lamp apart from being "alkaline," for it had a tubular bulb, with fittings so designed that it could be changed (see Fig. 4) without removing the contact plate. A machined bayonet joint was used to secure the upper to the lower part of the lamp. The accumulator was a separate component built up of two half-round nickeled-iron cells, flattened at the sides and welded together. The electrolyte filling holes were closed by solid screw plugs. The cell covers were welded on, and consequently the plates were inaccessible otherwise than by grinding off the top or bottom of the case. The battery had a closed-circuit voltage of 2·6 volts and a storage capacity of 8 ampere-hours when discharging at 0·7 ampere. The assembled lamp was 10 in. high and weighed 4 lb. 11 oz. The vulcanized-fibre contact plate, which carried segmental contacts on its under side and a lampholder and reflector on its upper side, was held in position by two screws, as shown in Fig. 4. The lamp was made with either a cylindrical or a dome cover-glass, a magnetic lock, and nickeled-steel pillars or the hinged horse-shoe which subsequently came to be known as the "pillarless" top. For the cylindrical glass type there was a nickeled conical reflector below the bulb and a nickeled cap above, coned and polished on the inside, which served the double purpose of reflector and dust-tight cover. Between this cover and the top of the lamp there was a wavy spring washer to allow of all the parts being tightly but elastically assembled.

In 1912 there was no experience to act as a guide to desirable strength of material, apart from knowledge gained in the manufacture and use of flame safety lamps; and such lamps must necessarily be handled gently, otherwise the light goes out. The first pressed-steel cases were not heavy enough, and began to wear out more rapidly than was desirable. Lamps were very roughly handled and were often dropped. The cases became indented and rusted at the base. A new type of shell was therefore made with double the number of ribs, and a strong pressed-steel ring was welded on to the base. Further experience indicated that the bottom was still not strong enough, and so, later in 1913, a low false bottom was added. The result was probably the first electric mine lamp with a reinforced base. In the same year, 1913, a larger model was made weighing 7 lb. and discharging at 1·5 amperes. It had a capacity of 13·5 ampere-hours and would thus be exhausted after about 9 hours. If at that time anyone had been prepared to try out a 7-lb. lamp it would have crossed the then imposed weight limit, and a much higher standard of mine lighting might have been set 25 years ago. The practice of making mine lamps with interchangeable heads to provide either all-round or beam illumination started with the 1913 model and has continued through the whole successive series. Extended experience having shown that there were many practical disadvantages in the use of a bayonet-jointed fastening, this was discarded in 1914 in favour of a square-threaded screw joint. Thus

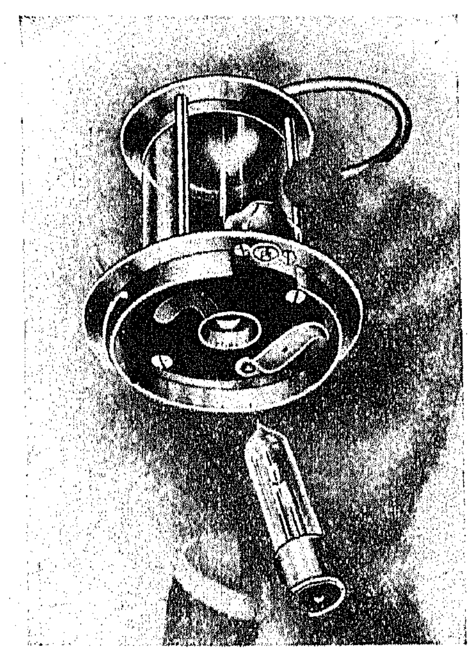

Fig. 4

originated a type of joint which is now common to many different kinds of lamps.

Difficulties with the tubular bulbs, arising mainly from inability to obtain a necessary standard of cleanliness and attention in colliery lamprooms, led to the abandonment of this interesting idea and reversion to the ordinary bulb and well glass. The year 1914 saw the appearance of a new form of case without ribs, and of much thicker steel. The lamp top was also strengthened. The battery output remained the same as in the earlier lamp. Then came the Great War, which resulted in the complete suspension of activities; for one of the many unexpected discoveries of that period of surprises was that there was no potassium hydroxide in the country wherewith to make electrolyte, and no nickel or active materials were obtainable wherewith to make new batteries. Thus there was a blank period from 1914 to 1919 during which no progress was made.

During early 1919 the general appearance of the lamp remained much the same except that the depth of false bottom was again increased, as a result of the observation that the majority of pick holes (and there were many in those days) were found just above the earlier low false bottom. The most serviceable depth and thickness of reinforcement were not evolved until after about 6 years' experimenting. First there was a $\frac{5}{8}$-in. welded ring, which was soon changed to a $\frac{5}{8}$-in. steel dish having the same contour as the original ring. The depth was increased from time to time, first to 1 in., then to $1\frac{1}{4}$ in., then to $1\frac{1}{2}$ in., and finally, about 1926, to $1\frac{7}{8}$ in. The later 1919-type lamps, Fig. 5, contained the first alkaline accumulators with flat sides and bevelled corners, the alteration being made to increase storage capacity.

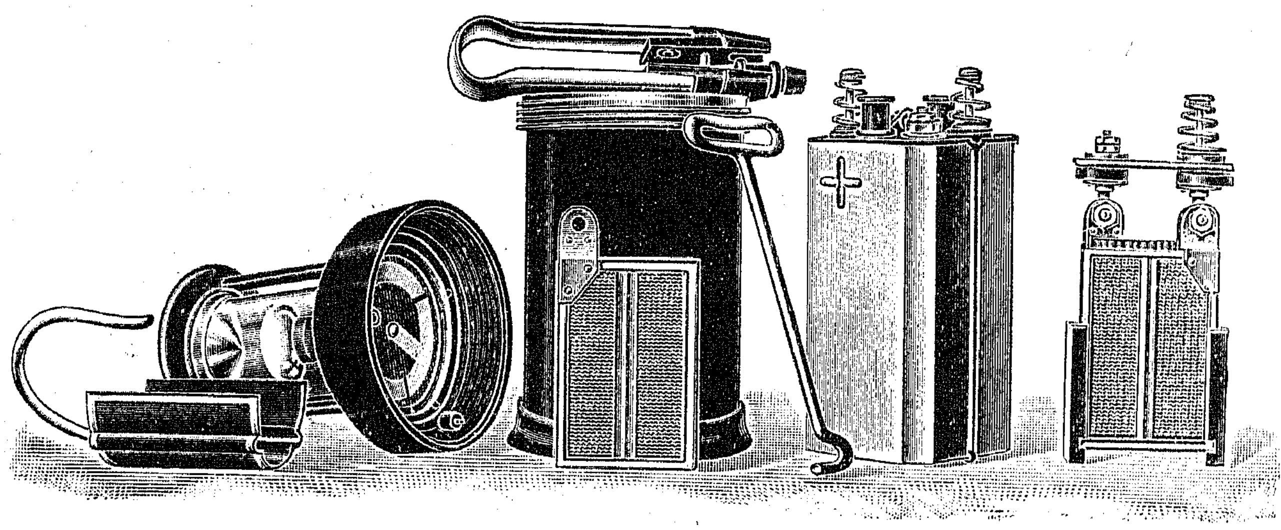

Fig. 5

### Stoppers and Valves

In the earliest alkaline accumulators the holes through which the electrolyte was poured were closed by solid screw stoppers, made watertight by washers. This was all in order according to the knowledge then available. Alkaline accumulators do not in theory liberate gases during discharge, and there was consequently no apparent reason for providing any vents. Under correct treatment, allowing batteries to stand idle for a sufficient length of time before closing the stoppers, there would be no internal gas pressure. In mine-lamp practice, however, it was observed that there *was* pressure within the cells, the explanation being that cells were very often taken off charge, the stoppers screwed down, and the batteries put into lamp cases, without any time being allowed for the gases liberated during charging to escape. This pressure either found relief through the washers, or caused dangerous spurting of alkali when the stoppers were next removed for charging. With solid screw plugs, moreover, there was always the possibility of forgetting to unscrew them before charging. Then the pressure in the cells would rise until something gave way: either the weakest joint would open or the case would bulge. If the plugs were not screwed down tightly enough there would be leakage of alkali, with possible unpleasant consequences. Also objection was made to the time cost of handling some thousands of stoppers every day.

The first substitute for the screw stopper was a specially shaped rubber cork (as shown on the battery in Fig. 5), and with it two new tools were devised—one for handling the rubber stoppers and the other for lifting batteries out of their containers. There had been some trouble in the lamprooms from alkali skin burns, and this was the primary reason for devising tools which would avoid the necessity for contact with alkali; the secondary reason being to increase the speed with which lamps could be handled. The bar which provided the series connection between cells was rolled up to form a tube, so that the battery could be lifted in and out of its case by means of a hook, one of which is shown resting against the battery case in Fig. 5. The stopper handling tool shown on the top of the lamp case was also devised, to prevent direct finger contact with stoppers.

The rubber corks became slippery by contact with the electrolyte, and had to be abandoned. A bayonet-jointed plug was next devised in which there was provision for the release of undue pressure of gas. Another tool was invented to allow of fixing and removing these plugs without bringing the fingers into contact with alkali. In this model helicoidal flat spring terminals were first used. Next there was designed a screw plug with a valve which could be opened and closed by movement of an eccentric lever. This device proved to have some practical disadvantages, and an effort was made to produce a stopper which would automatically relieve excess gas pressure, and at the same time expedite lamproom operations. The first form in which this ap-

peared is almost sufficiently explained by Figs. 6 and 7, which show a conical sealing plug held on its seating by spring pressure, the spring being carried in a tubular hinged bracket welded to the side of the battery case. This improvement was evolved about 1919 but seems to have been first used in the lamps (still in use) which were installed at Wallsend and Hebburn Collieries in 1921. Each stopper had to be lifted separately and, although this was only a momentary operation, it was soon realized that the opening and closing time would be reduced by half if the two stoppers could be moved simultaneously. The two plugs were thereupon mounted on a rotatable bridge which held them on their seatings by spring pressure, and which could be raised vertically against the

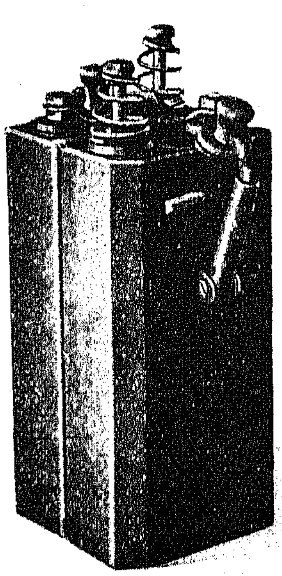

Fig. 6

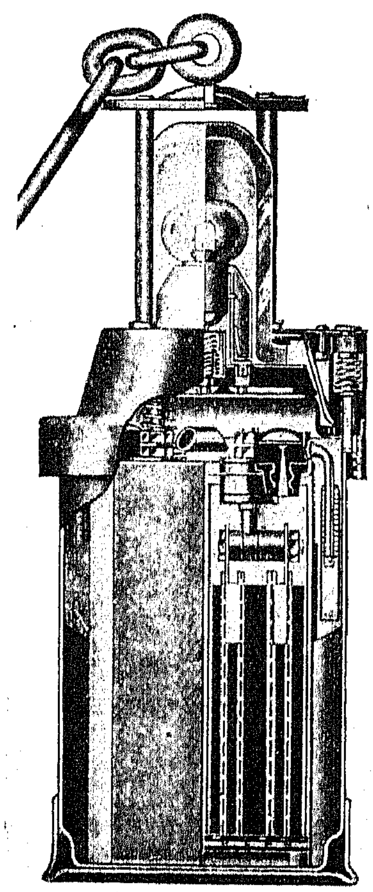

Fig. 7

resistance of the spring to lift the plugs out of the filling holes. Yet another kind of tool was devised for lifting and turning the bridge so that the operations of opening and closing the two filling holes became simultaneous and almost instantaneous. This system was first put into service at the Birchenwood Collieries, Kidsgrove, in 1924. It continued to be used until superseded by a valve plug with a rubber diaphragm having a pinhole in its centre. The idea here was to devise a valve that would allow gas to escape without the necessity for removing or even loosening the plugs, and yet be watertight.

In order to compensate for loss of electrolyte through gassing and evaporation it is necessary to add water or weak electrolyte periodically; in mine lamps this means about once a week. In the case of lead-acid lamps the electrolyte level (in wet-acid lamps) could be ascertained by simple observation through the transparent celluloid. With an alkaline battery it could only be determined by removing the plugs and looking into each of the cells, or by dipping with a piece of laboratory glass tubing. Ocular observation was not very easy in a colliery lamproom of the period, the dominant characteristic of which, always excepting dirt, was darkness. Tube testing was slow. A metallic extension to the stopper, which dipped into the electrolyte and only just cleared the tops of the plates, was therefore evolved. This metallic extension, Fig. 8, was tapered in such a way as to give a resistance depending upon the level of the electrolyte, between the stoppers and the lamp case. A suitable testing tool was devised which consisted of a two-pronged fork with bulb in series connected with a portable battery. The prongs were applied respectively to the head of the stopper and any part of the battery case. If the bulb failed to light the indication was that there was no circuit through the electrolyte and that, consequently, the cell needed to be " topped up " at once. If the bulb glowed dull red the electrolyte was down on the tapered part of the plug extension and would soon need attention. If it glowed

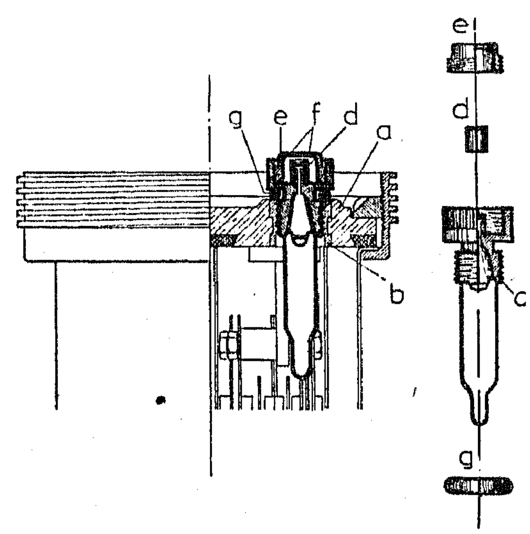


Fig. 8.—Combination valve filling hole plug and electr level indicator.

(a) Ebonite cover plate.
(b) Screwed iron bush moulded into cover plate.
(c) Valve plug with level indicator.
(d) Valve tube.
(e) Screw cap.
(f) Gas vents.
(g) Rubber stopper washer.

brightly no " topping up " was necessary. In practice a lampman quickly learned to estimate when " topping up " would become necessary. The valve itself was subsequently improved by taking away the rubber diaphragm and substituting a bicycle-type valve, Fig. 8, in which a metal stem was bored longitudinally, and at the top end a small hole was drilled horizontally through it, to meet the vertical hole. The metal stem was covered by a thin rubber tube, covering the horizontal hole. This made a watertight joint, and at the same time allowed the gas to force itself up the side of the rubber tube and escape through pinholes in the protecting cap. The combined device has now been in use for about 14 years.

### Prevention of Alkali Leakage

The production of an alkaline lamp that will not leak is a matter of great practical importance, owing to the corrosive action of the caustic-potash electrolyte on the skin. The tendency of the electrolyte to " creep " and to leak at joints has been gradually lessened by improve-

ments in the design of battery cover-plates, of filling-hole stoppers (as above), and of the means whereby terminals are attached to the electrodes; by the correct proportioning of air space in the cells; by the adoption of various means for the prevention of inter-cell leakage; and by the development of a suitable charging and handling technique. By 1921 it had become evident that a welded-in accumulator was comparatively useless for mine-lamp service. In theory (and also in practice where batteries are not liable to rough handling, insufficient charging, and over-discharging) an alkaline accumulator has a very long life, this being in fact one of its outstanding characteristics. It has become a stock claim that the life of an alkaline battery is 10 years: such a claim may be either true or untrue according to the context and the implications. A large stationary battery, or one with a reserve capacity greatly in excess of the demands made upon it, may very well last 10 years or more: but in a mine lamp, where surplus storage is limited to the weight which it is practicable to carry, where the conditions of use are entirely different from those obtaining in non-portable accumulators, where the batteries may be completely discharged daily, and where a proportion of them may be constantly called upon to work far beyond their rated capacity, the 10-year-life claim has a varying but always lesser degree of validity. There are, however, many advantages in the use of alkaline lamps apart from relative absence of plate renewals. This is sufficiently proved by the fact that, notwithstanding the very much higher capital outlay involved, all the great mine-lamp hiring firms in the world use only this class of lamp.

### THE TWO-PART ALKALINE LAMP

Miners' lamps are often dropped, or allowed to fall off props. Lamp cases are bruised, crushed, and pickholed. They are hung on pit tubs and banged about, rather than merely being subjected to vibration. Batteries are often damaged by gross neglect in lamprooms. They are sometimes charged when half dry, and when alkaline lamp batteries are used in the same lamprooms as acid lamps it is not unusual to fill them with sulphuric acid. Such accidents and conditions inevitably necessitate opening out the cells, and it is obviously more convenient and cheaper that a lampman should be able to open a battery himself and make the necessary repairs rather than send it back to the makers. With these and other considerations in mind an attempt was made, early in 1922, to produce an alkaline battery which could be opened, repaired, and reassembled by an unskilled man.

The idea of a built-in battery accessible for repairs was not new in itself. Even before the War experiments were being made with batteries assembled in lead-lined steel cases, but with free-acid electrolyte it was found impracticable at the time to prevent leakage. The leakage problem automatically solved itself when the use of jellied electrolyte became common practice. The earliest two-part lamps with removable cover plates were lead-acid lamps of the unipolar type. They had a rigid positive terminal with a double spring plunger inside the lampholder, the case being earthed to get the negative contact. In 1920 the Concordia Co. of Dortmund carried the two-part construction a stage further by the invention of their concentric contact system. Cylindrical pasted-lead elements were assembled in pairs complete with rigid concentric contacts. These were dropped on to suitable cell-rests in a lead-lined steel case and secured therein by means of a lead-coated steel cover-plate held down by a steel spring ring which fitted into a groove cut into the inner wall of the screw-threaded joint ring. A combination lampholder with spring-controlled concentric serrated contacts made contact with the battery poles when the lamp top was screwed home. Thus, instead of three separate parts—battery, battery case, and lamp top—the new lamp had only two, and the labour and space necessary for handling the lamps was correspondingly reduced. The celluloid fire risk was also eliminated, and the concentric-contact system prevented any inadvertent reversal of current when placing cells on the charging stands. This invention constituted the only radical change in the design of lead-acid mine lamps which had been made since they first came into general use. The author was associated with the Dortmund firm in introducing the new invention, which became known in Great Britain as the "Federation" two-part lead-acid lamp. A lamp of this type is shown in Fig. 9.

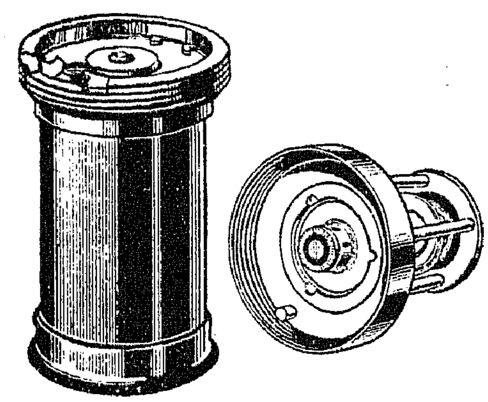

Fig. 9

The evolution of a two-part alkaline lamp was an entirely different problem. A single alkaline cell has a voltage of only about 1·25 volts, which is useless for any practical purpose. Consequently, it has always been necessary to join two cells in series in order to get an effective working voltage. There was originally considerable difficulty in making a cylindrical steel case with a central partition which was absolutely gas- and alkali-tight and which could be effectively sealed by means of a detachable cover-plate. Every imaginable way of making such a lamp case was tried out before it became practicable to standardize a satisfactory constructional form and manufacturing procedure. It was not until the partitioned cylinder with electrodes assembled on the cover plate had been in very extensive use all over Europe for at least 4 years that any other two-part alkaline lamp appeared. The first 1 000 two-part alkaline lamps were installed at Birchenwood Collieries, near Kidsgrove, in April, 1924. The design was subsequently improved by the use of a newer type of valve plug and improvements in the cover-plate itself. The cover plate, being made of ebonite, was automatically free from surface leakage between terminals, which is an occasional source of trouble in metal cover-plates. Leakage of electrolyte through loose terminal stalks was

made impossible by moulding them in the ebonite. Electrolyte leakage between battery and cover plate was minimized by providing a broad machine-faced seating for the joint. No other leakage path remained except through the stoppers themselves, which might at times not be sufficiently screwed down. The stopper washers were originally flat, and tended to spread after a time owing to the action of the alkali. Round rubber rings were therefore substituted, and the upper and lower seatings were inversely coned. This prevented the washers from spreading. The general effect of many such small changes in details resulted in the production of a non-leaking and, as to its external surfaces, a practically dry battery. Only abnormal conditions, caused, for example, by over-filling the cells, by an internal electrical leak, or by neglect to keep the valves and seatings in good condition, could now disturb the normal functioning of the battery. Any such abnormal condition, being observable during charging, could be remedied before the

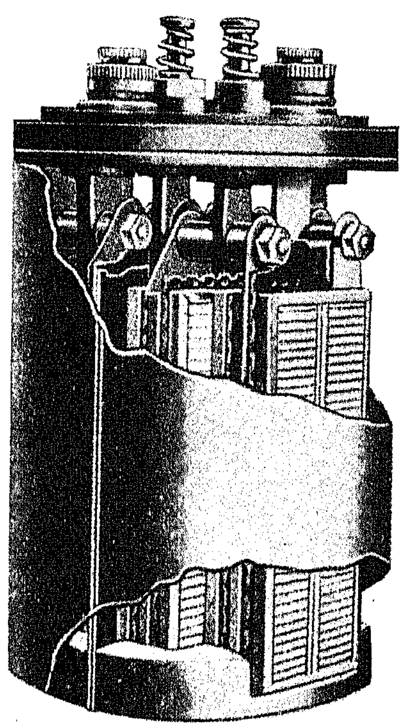

Fig. 10

lamp was sent out. The improved construction is indicated by Fig. 10, which shows the assembled battery plates. Over-filling being a fruitful source of alkali trouble, an automatic filling tool was evolved from which electrolyte ceased to flow and in which an indicator bulb glowed when the correct level was reached.

## DETAIL IMPROVEMENTS

The contact plates through which current from the battery is passed to the bulb were originally of vulcanized fibre, with two segmental metal contacts screwed into grooves machined in the insulation. Fig. 4 illustrates this construction. The method of securing the contact plate by means of a screwed steel ring was first used in 1913.

From early days it has been usual to switch mine lamps on and off by rotating the upper part of the lamp, carrying the contact plate and lampholder, against the lower part carrying the accumulator. This switching operation caused grooves to be worn in the vulcanized fibre by the terminals, which then jammed against the edges of the segmental contacts. Attention was therefore turned to the use of ebonite with extra segmental rubbing plates between the current-carrying sections, as in the lamp top shown in Fig. 5. Originally, the ebonite was turned in the lathe and grooves were machined on the outer face to fit the metal segments, which were attached by screws. At a later date the author's firm originated the now common practice of moulding all the metal parts into the ebonite.

It was also in Wolf lamps that the various slotting systems for controlling the switching and locking of lamps were first completely developed. In the earliest lamps a simple rectangular slot was cut into the rim of a battery container and the lock plunger dropped into this slot when the lamp top was screwed home, there being sufficient play in the lock to allow of switching on and off. The practical disadvantage of this device was that in order to avoid locking the lamp *before* the top was screwed home the bottom had to be screwed into the top while the plunger was held up against the magnetic unlocker. This was a comparatively slow operation. In 1919 the slotting of the case was altered to allow of a lamp being locked, tested for light, switched off again, and finally locked with the light " on." In such a lamp case a V slot was cut on one side of the rim and a rectangular slot on the other. The lampman assembled the parts and screwed on the top until the lock plunger clicked into the V slot. The lamp was then " off," but a slight additional turn switched it " on." If it burned properly it was switched off and left until wanted. When the lamp was handed out for use another half-turn was given to the top, and this carried the plunger into the long slot. The lamp was then locked " on," and remained " on " until it was returned to the lamproom. The reason for developing this particular locking system was that the vacuum drawn-wire bulbs which were in use from 1912 until about 1928 were very sensitive to shock when cold, but strong enough when incandescent. It was thought that if the light was never switched out during use the bulbs would have a longer working life. The device served its purpose at the time, but subsequent improvements in bulbs removed the necessity for it.

In some countries it is common practice to make mine lamps without switches. It is, however, doubtful whether there is any advantage in using switchless lamps and there are several reasons why switch lamps are to be preferred. One is that, in the event of an underground accident imprisoning a number of men, light can be maintained for nearly as many days as there are lamps, if they are all switched off except one. Another is that falls of roof have been known to break lamp glasses and bulbs and short-circuit the filament supports. In such an emergency the current should be cut off as quickly as possible. A third reason is that where lamps are working to the margin of their capacity as, for example, in unavoidable overtime, they will maintain their light better if switched off at meal times. Incidentally, the practice of switching off at meal times as many lamps as convenient would, if made a daily habit, lengthen the useful life of the batteries and provide a higher average illumination. Some lamp batteries are designed with a large margin of capacity in relation to their rated output, but there are others in which the margin is very fine.

The next change in the slotting system arose out of troubles with magnetically-operated lamp locks. The idea of switching a lamp on or off by rotating the upper part, carrying the contact plate, against the lower part, carrying the terminals, probably began with the invention of the first serviceable magnetic lock. Mine lamps are required by law to be locked when in use, and many attempts have been made to devise suitable magnetic locks. One of the earliest was the Craig and Bidder lock of 1869, designed, of course, for use with flame safety lamps. In France, Mueseler flame safety lamps had magnetic locks before 1877, but no such type of lock came into extensive use until after the invention of the Wolf lock, which was first applied to the benzine flame safety lamp of that name. The first magnetic lock to be used on an electric lamp seems to have been of the same spring-plunger type as those in common use to-day. The author has not been able to trace any earlier magnetically-locked electric mine lamp than the Wolf–Bohre models of 1904–05. In these models the lock was mounted horizontally on the rim of the lamp top, following Wolf flame-lamp practice. In later lamps it was mounted vertically, so that the lock plunger ran on the rim of the battery case when the parts were being assembled, and then dropped into a slot which restricted the movement of the lamp top relative to the battery case in such a way as to allow the contacts to be moved from "live" to "dead" points, or in the reverse direction, without causing the parts to become detached. One of the earliest troubles was caused by the lock plungers sticking. Either the lamp failed to lock or it could not be unlocked. The cause was dirt, but lampmen had little or no experience of electric lamps, and they could rarely be induced to keep the lamps sufficiently clean. In the effort to overcome this difficulty a greater variety of locks was made than most people have ever seen—round locks, square locks, slotted locks, chisel-edged locks, and so forth. It was several years before a permanently satisfactory form was evolved. About 1921 the author's company developed the practically dirtproof locking system, to which they have since adhered, and which, in principle, is to be found in most of the alkaline lamps which have come on the market since 1927. The idea was to make the lock plunger climb over an anticline which was cut into the rim of the lamp vessel between the respective "on" and "off" positions. By giving the lamp top a few quick backward and forward movements a sticky lock plunger was eased, and if it was left standing on the top of the anticline when applied to the magnet it would be halfway towards being unlocked, and the magnet could pull it so much more easily. Nothing now but gross neglect can cause a lock to stick in lamps thus designed.

The evolution of the two-part alkaline lamp necessitated a change in even such a seemingly insignificant item as the number plate. So long as the battery remained an independent unit, number plates could be secured by rivets. When the built-in battery system was developed it became impossible, on account of leakage, to attach a number plate by riveting, and soldering was equally impracticable. Moreover, lamp numbers sometimes need to be changed at the colliery. The author's company therefore originated the now familiar frame with a detachable number-plate which could be sprung in and removed again when necessary.

The external appearance of lamps has continuously changed during the years of development. In the early lamps the cover glass was made as small as possible, the upper extremity to which the pillars were riveted was a disc, and the pillars themselves were set parallel to and very close to the glass. The consequence was that these lamps cast heavy shadows. As time went on and more attention was paid to illuminating values the protecting glasses became larger, the pillars were set farther apart and set slanting, and the upper plate to which the carrying handle is attached was made first square and afterwards with the sides incurved, to increase vertical light distribution. Most of these stages in the external appearance of lamps may be observed in the successive illustrations accompanying this paper.

## THE EVOLUTION OF THE HIGH-CANDLE-POWER LAMP

The advance so far indicated has dealt only with the evolution of essential details of design. The lamps had become more and more reliable and easier and cheaper to handle, but there had been no progressive increase in candle-power. At various times between 1913 and 1925, materially higher-candle-power alkaline lamps had been made, but they had not been wanted. There were, it is true, one or two of the box-type lead-acid lamps being made in 4-volt 1-amp. form, and it is probable that the Gray–Sussmann "Type 4" lamp was actually the first in the class subsequently to be known as "high-candle-power lamps" to be approved by the Mines Department for general use. This model was made in 1923. Nevertheless, acceptance of higher-candle-power lamps by the mining industry came only by very slow stages and mainly out of the necessity for more light enforced by increasing mechanization. Until 1926 no one, either at home or abroad, would consider a much heavier or bulkier miners' lamp than they were using. There was no noticeable appreciation of the economic value of light; by no means general belief in better lighting as a remedy for nystagmus; scarcely any conviction that still better lighting would improve the quality and quantity of coal produced and reduce accident risks; and almost imperceptible realization that a great increase in the amount of light in the working places, even though accompanied by increased lighting costs, would eventually reduce the overall cost of producing a ton of coal.

From 1912 to 1925 the rating of the alkaline lamp had remained at 2·5 volts and round about 0·7 ampere, while the 2-volt lead-acid lamp had stood at about 0·85 ampere. In the year 1925 the original two-part alkaline lamp was enlarged to 12 ampere-hours capacity and the weight increased to 7 lb. 11 oz., with a discharge rate of 1 ampere. This marked the first stage of progress towards substantially higher-candle-power lamps. The value of the improvement represented by the 1925 lamp is clearly shown in a paper by Prof. W. H. McMillan on "Light Distribution from Miners' Electric Lamps,"* which was read on the 18th January, 1927, at University College, Nottingham. In Fig. 11 (reproduced from Fig. 4

* *Proceedings of the National Association of Colliery Managers*, 1927, vol. 24, p. 55.

in Prof. McMillan's paper) the horizontal polar light curves lettered R, S, and T represent the three best-known 2-volt lamps, and curve P that of the Wolf alkaline lamp. Noting, however, that useful illuminating value cannot be represented by curves of horizontal light distribution, Prof. McMillan plotted a series of vertical

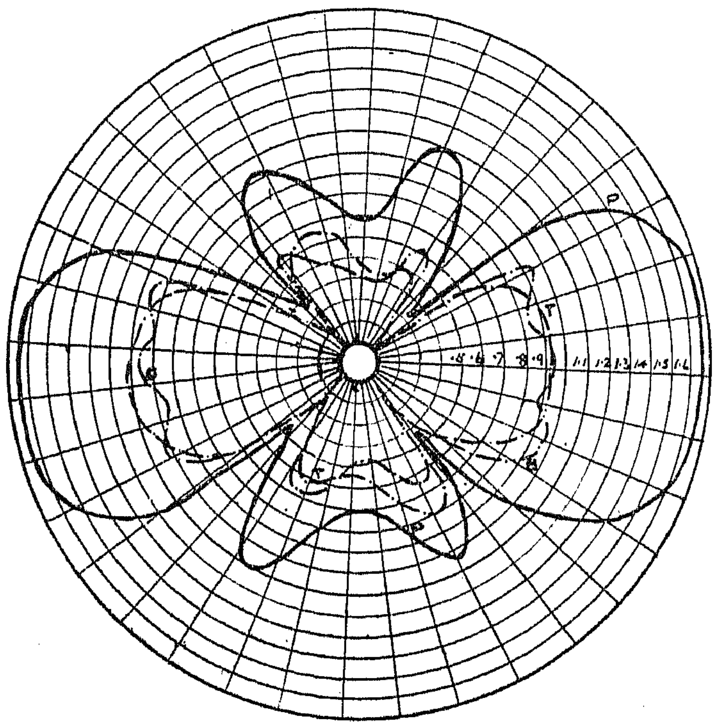


**Fig. 11**

polar curves with the filaments broadways and another series with the filaments edgeways. These two sets of curves are averaged in the Russell diagram, Fig. 12 (Fig. 7 in Prof. McMillan's paper). The average overall candle-power figures were: Lamp P, 1·11; lamp R, 0·55; lamp S, 0·70; lamp T, 0·63. It appears, therefore, that the 1925 alkaline model registered a 76 per cent increase in effective illumination over the average of all the other lamps in major use.

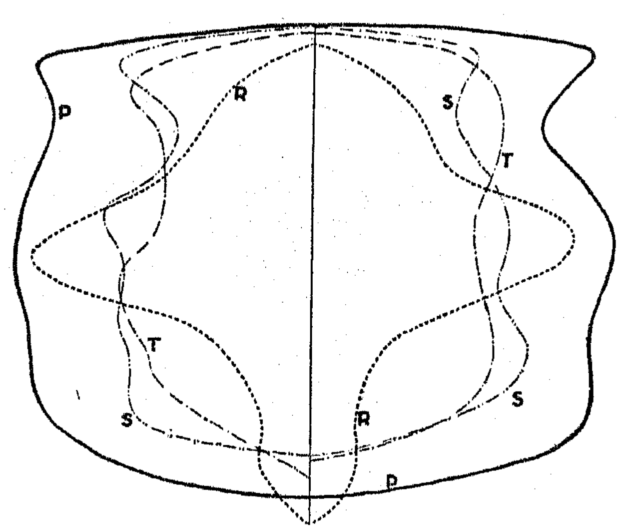


**Fig. 12**

In 1926 the author's company were asked whether they could not improve on the light given by the 1-ampere lamp. Thereupon a larger lamp was made to get increased capacity and to level up the discharge curve, still using 1-ampere bulbs. The 1926 model was followed in the same year by one of 18-ampere-hour capacity, and another of 22-ampere-hour capacity, each discharging at 1·5 amperes. Practical trials had proved that the supposed objection of miners to carrying a much heavier lamp was non-existent.

A few lamps of lesser output with flat-plate Edison accumulators had been tried by various lamp-makers, and a considerable number of Pearson " Nife " lamps had come into use in Great Britain. It had, however, become evident that the 2-volt lamp was out-dated, and various efforts were made to design 4-volt lead-acid lamps comparable as to illuminating values with the new-style alkaline lamp. Early in 1925 Mr. Hodgkiss, manager of the Aldwarke Main Colliery, near Rotherham, began experimenting with 4-volt acid lamps, and between that year and 1929 he evolved and equipped his colliery with what was known as the " Aldwarke " lamp. It weighed $7\frac{1}{4}$ lb. and when new gave a mean horizontal candle-power (M.H.C.P.) of 2·4.

The first large-scale production of 4-volt lamps was due to the Concordia Co., of Dortmund, who in 1926–27 made a 4-volt lamp embodying those principles of design which had been successful in their two-part 2-volt lamp but with the elements in celluloid instead of in leadlined steel cases. In late 1927 there were between 8 500 and 10 000 of these 4-volt lamps in use in Holland and Germany. They were eventually largely discarded in favour of alkaline lamps. In Great Britain a corresponding effort to provide an alternative to the high-candle-power alkaline lamp was made somewhat later by Oldhams and other lamp makers. Since about 1930 the difficult problem of preventing inter-cell leakage and maintaining voltage has received continuous attention, and the 4-volt mine lamp is now (as to Great Britain only) a recognized competitor of the alkaline lamp.

In 1927 the Concordia Co. commenced to make an alkaline lamp on the concentric-contact system already described. They adapted this system to the Edison tubular positive-plate arrangement, and by using Jungner-type negatives obtained a nickel-cadmium accumulator. This lamp (shown in half-section in Fig. 13) was first approved by the Mines Department in February, 1930. By this time it was becoming an established type abroad.

Side by side with these progressive increases in the size and output of alkaline lamps experiments were being made with better bulbs and cover glasses. The wire-drawn vacuum bulbs lost light-transmission values by blackening, and means were sought of reducing the light loss. The author's first attempt (in 1928) was to have bulbs blown of extra-large size, with the idea of increasing the electron path and so stopping the bombardment of the glass. Larger lamp-tops and frosted prismatic well glasses having an inside diameter of 52 mm. were made to suit these " balloon " bulbs, but they were never used except for experiments. The explanation for this is that within a few months it was possible to obtain gasfilled bulbs. The earlier vacuum wire-drawn bulbs had inverted-V or arched filaments, which gave maximum or minimum light values according to whether the filament was seen face on or end on. The first gasfilled 2·5-volt mine-lamp bulbs were " Nitra " bulbs with horizontal spiral filaments mounted on stout wire supports. The relatively intense light, concentrated almost to a point, gave strong shadows from the supporting wires, and

intensified glare. Capt. C. B. Platt, the chief testing officer of the Mines Department testing station at Sheffield, made the suggestion that the problem would be largely solved if the filaments could be mounted vertically. The author thereupon, also in 1928, had a supply of gasfilled vertical spiral-filament bulbs specially made, and continued the Lancashire experiments with them. This was the beginning of the regular commercial use of gasfilled bulbs with vertical filaments in Wolf lamps.

A year earlier, Vernon* had suggested making 2-volt vacuum bulbs with vertical filaments and had referred to a 4-volt gasfilled bulb but without indicating its construction. Still earlier (June, 1925) a few experimental 4-volt gasfilled bulbs had been made for Capt. Platt by

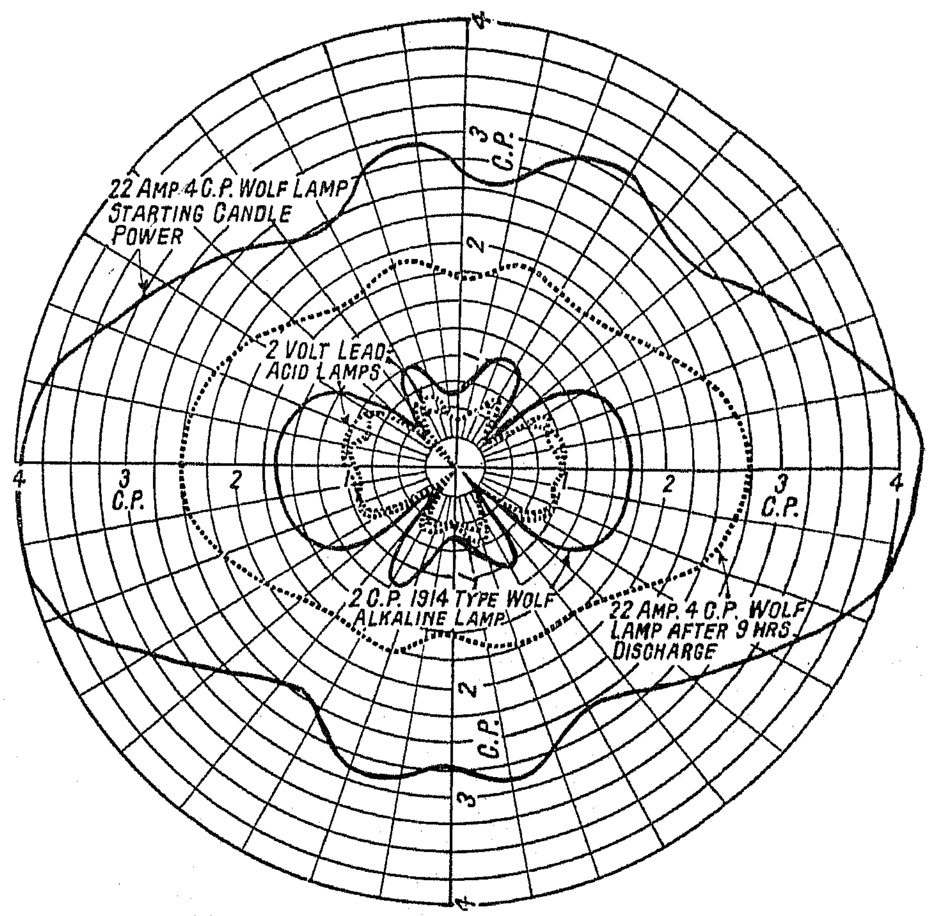


Fig. 14

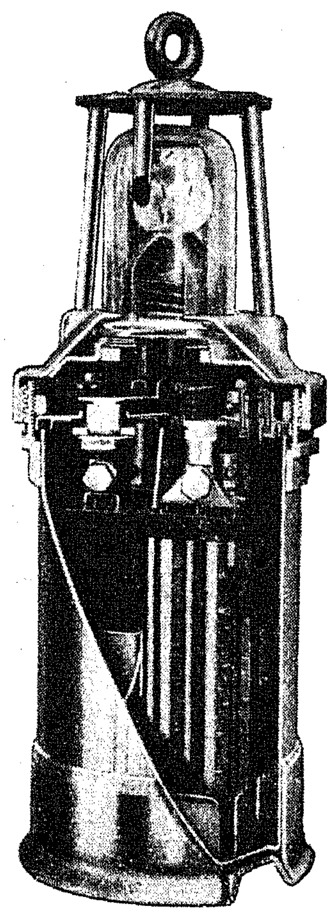

Fig. 13

the Edison Swan Co., for trial in the Aldwarke lamps, but it was not until 1934 that the 4-volt 0·75-ampere gasfilled bulb became a standard type, and 1936 before the 2·5-volt 1·5-ampere gasfilled bulb was standardized for use in all suitable alkaline lamps (see B.S.S. No. 535—1936).

The 2·6-volt 1·35-ampere gasfilled vertical spiral-filament bulb was an immediate success. The vertical-filament bulb is now used throughout the mining world, and has served to improve the light distribution of the miners' electric hand-lamp to a greater extent than any other single idea.

From about 1920 onwards various efforts were made to produce a more diffused light by the use of frosted and opalescent well glasses. Experiments were also made with coloured glass, and in 1923 a certain yellow-tinted glass began to have a vogue in 2-volt lamps. Early in 1927 the author's company introduced a new prismatic well glass, lightly frosted. The practical effect of using this type of

* *Colliery Guardian*, 1927, 18th and 25th March and 1st April.

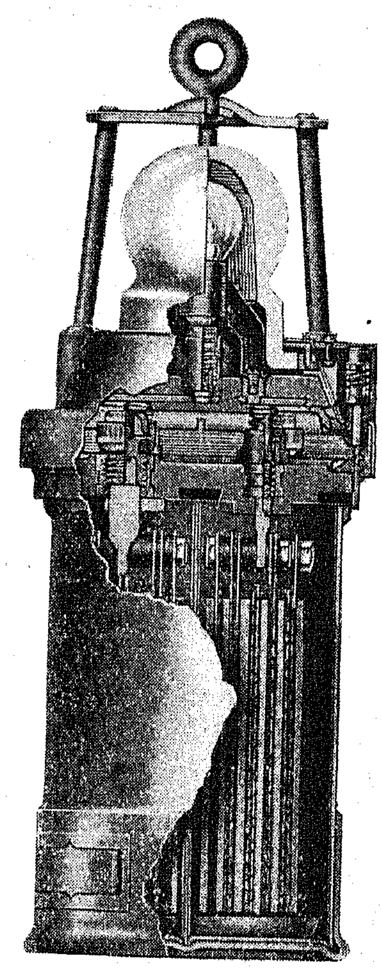

Fig. 15

glass was to cut out pillar shadows and to change the polar curve of light distribution from the butterfly curve, showing four dark points (Fig. 11), to the new curve, which indicates that shadows have almost disappeared. The polar curves, Fig. 14,* indicate the further extent of

* Reproduced from *Colliery Engineering*, March, 1930, p. 104.

the improvement made in illuminating values up till 1926, and, incidentally, the effect of the prismatic glass on the distribution of light. The inner series of curves are as in Fig. 11, and represent the progress made up to 1925. The outer curve is that of the 22-ampere-hour lamp discharging at 1·5 amperes. The largest of the dotted-line curves indicates the light values of the same lamp after 9 hours' discharge. These candle-power curves do not represent actual illuminating values as they are determined to-day: mine-lamp photometry was then in an elementary state, and the data merely indicate comparisons made under the same test conditions.

September, 1930, saw the first commercial appearance of a new cover-glass, designated the "ball" glass. This glass is fitted to the lamp shown in Fig. 15. It had internal vertical prisms around the wall and concentric prisms in the crown of the glass. It was lightly frosted. The effect of this glass was to intensify the all-round horizontal distribution of light, and give the lamp a higher effective illuminating value in the directions where light was most wanted. It is specially useful in seams not exceeding about 3 ft. 6 in. in thickness.

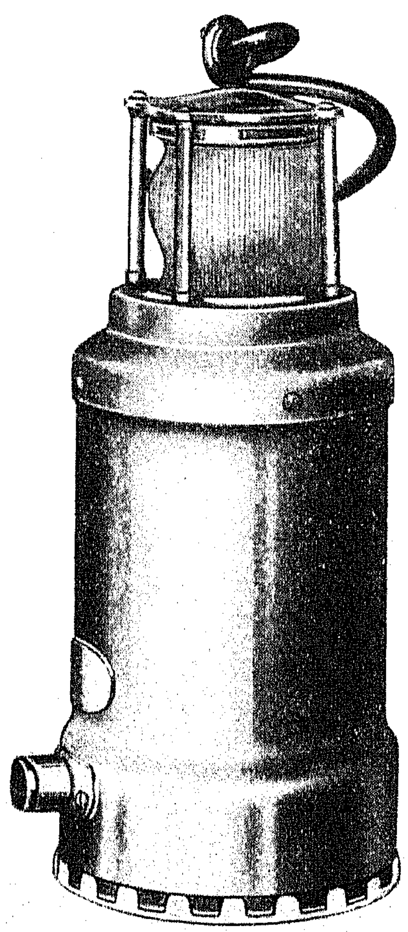

**Fig. 16**

In 1931 a lamp was produced with a capacity of 28 ampere-hours and a discharge rate of 2 amperes. This at once became a standard model. A still newer model, made early in 1935, is 12 in. high and weighs 10 lb. 6 oz. It has a capacity of 35 ampere-hours and is designed to maintain an average end-of-shift M.H.C.P. of 4. The lamp which is claimed to have started the revolution in mine lighting is represented in its present "Schedule A" form by Fig. 15. Fig. 16 illustrates, as a representative example of a modern 4-volt lamp in the same official classification, the Oldham "Type S."

## ELECTRIC MINE LAMPS WITH FIREDAMP INDICATORS

The only serious objection to the universal adoption of electric lamps in substitution for flame safety lamps is that they give no warning of dangers arising from the presence in the mine air of noxious or inflammable gases. The desirability of incorporating in an electric mine lamp the means of detecting firedamp was recognized even before the electric lamp itself was sufficiently developed, and in 1911 Mr. G. J. Ralph described the Holmes–Ralph gas-detecting portable electric lamp. Despite the fact that inventors all over the world have been trying to produce a satisfactory combination lamp for at least 25 years, there is no such lamp in appreciable use. The most reliable gas-testing electric lamps have hitherto been those in which an electric lamp is structurally combined with a miniature flame safety lamp. Prof. Thornton has, however, recently developed a basically new idea.*

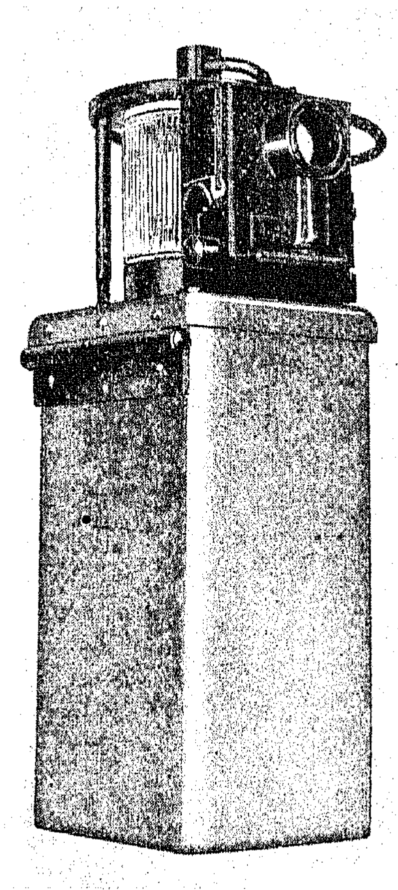

**Fig. 17.**—Thornton firedamp detector fitted to Gray electric safety lamp.

The Thornton firedamp detector was last year approved by the Secretary for Mines for use under General Regulations (Firedamp Detectors), 1935, when fitted to the Gray 4-volt lead-acid lamp. In the official announcement it is stated that "this detector, which is attached to an electric safety lamp of approved type, and can be set in the lamp-room to enable the user to detect either $1\frac{1}{4}$ or $2\frac{1}{2}$ per cent of firedamp has, after a long period of experimental development, passed the official laboratory tests, and has also given satisfactory results in pit trials. It is therefore now approved under the Firedamp Detector Regulations in order to give colliery

* See *Transactions of the Institution of Mining Engineers*, 1932–33, vol. 85, p. 335.

owners full scope for investigating its more general application and development in mining practice." Fig. 17 illustrates this lamp.

As a new incentive to the invention of mine lamps in this class the Central Committee of the Mining Association announced in December, 1936, the offer of a prize of £500 for the best design of an automatic safety lamp that would not only give an unfailing signal of the presence of firedamp but would also provide the maximum illumination for working purposes at the coal face. An analogous offer was made by the Prussian State mining authorities in 1922. It remained open until 1924, and awards—in the nature of consolation prizes—were made in 1925.

## COAL MINES GENERAL REGULATIONS (LIGHTING) OF 1934

Reference may perhaps usefully be made here to the new mine lighting regulations which became obligatory as from the 1st January, 1937.

In December, 1930, the Mines Department issued to the interests concerned a circular letter wherein they drew attention to "the outstanding importance of better lighting below ground in the prevention and cure of miners' nystagmus and in the prevention of accidents, and of lighting generally as a factor in efficient and economical working." The ultimate outcome of this notification was the issue of the Coal Mines General Regulations (Lighting), 1934. These Regulations represent the first legislative change in the test conditions required for the approval of new miners' lamps which has been made during the last 25 years.

They classify lamps into two groups known respectively as Schedule A and Schedule B. Schedule A lamps may be used in any part of a mine but *must* be used in certain specified parts. They are of the class commonly referred to as high-candle-power lamps. Schedule B lamps (omitting reference to subsidiary classifications) are intended for the use of persons other than those employed at the working face and adjacent thereto. The new regulations embody conditions as to intensity and distribution of light, and battery performance, and restrict the use of bulbs to those which comply with British Standard Specifications for miners' hand-lamp bulbs, or, lacking a British Standard Specification, have been approved by the Secretary for Mines. Also, for the first time in the history of the Mines Department, they specify certain conditions of maintenance for electric mine lamps. It was owing to the development of the high-candle-power alkaline lamp, to improvements in the illuminating value of flame safety lamps, and to the later successful efforts to produce 4-volt lead-acid lamps of equivalent lighting value, that the Mines Department found it possible to propose, and eventually establish, this most desirable revision of mine lighting regulations.

# DISCONTINUOUS PHENOMENA IN RADIO COMMUNICATION

By BALTH. VAN DER POL, D.Sc.

(*Lecture delivered before the* WIRELESS SECTION, *7th April*, 1937.)

## (1) INTRODUCTION

In this lecture I propose to discuss some questions and problems relating to discontinuous phenomena in radio communication, and, as the idea of discontinuity is typically a mathematical one, it will be clear at the outset that what I shall say will be closely related to some theoretical aspects of radio science. There may be no objection to this, however, for experience has shown that, especially in a science like radio communication, which has so many branches developed to a high degree, a deeper insight into what really occurs in our experiments may be of the greatest practical value for further developments. In this connection I may quote Boltzmann, who remarked: "There is nothing so practical as a really good theory."

However, while developing some theoretical considerations, I shall remain in very close touch with the physical realities; but, in treating the subject in this way and having, moreover, regard to the vastness of the subject, it will not always be possible to include a complete derivation of the expressions given. Further, I shall base my treatment of the subject, as regards rigour, on the usual standard of a theoretical physicist, which, perhaps, corresponds to the arithmetical mean of the rigour of the abstract mathematician on the one hand, and that of the practical technician on the other.

Discontinuity, as I have said, is a mathematical fiction, and it may be queried whether discontinuities in the mathematical sense occur in nature at all. I shall not attempt to answer this question to-night, but what I should like to stress is that, if we are concerned with physical systems, and the value of one parameter—to fix our ideas, consider a constant e.m.f. suddenly inserted in a circuit—is in a very short but finite time increased by a certain finite amount, and, moreover, if this time is short in comparison with the shortest time-constant or the shortest characteristic period of the system, then we may treat this actually *continuous* phenomenon with *discontinuous* mathematical methods. For, considering again the quoted example of suddenly inserting a constant e.m.f. in a circuit, it will be clear that it is physically impossible to imagine a way of applying this e.m.f. in a really infinitely short time, because, as the two parts of the switch approach each other, we can consider them as constituting a condenser, the capacitance of which is increased in a short but finite time, say $t_1$, from a value $C_0$, say, to infinity. This change of capacitance will already have caused currents to be set up in the system before the wires actually touch. However, if the duration $t_1$ is small with respect to the smallest values of $L/r$, $CR$, or $(CL)^{-\frac{1}{2}}$, or a combination of them belonging to the circuit, in most cases the error caused by considering the experiment to be discontinuous in the mathematical sense will be negligible.

Now it may be asked whether there is, theoretically, any advantage in more or less forcing a phenomenon, which in reality is *continuous*, to be *discontinuous*, remembering that the commoner mathematics operate with differentials and differential equations and thus could be said to show a "*horror discontinuitatis*," just as the old physics presented the well-known "*horror vacui*." The answer to this natural question might be given in the following way: Although it is true that the older analysis—in the days when the ideal potential functions, being the smoothest functions imaginable and satisfying $\nabla^2\phi = 0$, were so much studied—actually disliked discontinuities, more modern analysis (e.g. Fourier series admitting discontinuities, the Stieltjes integral, integral equations, etc.) does not show this dislike to such an extent. As a practical electrotechnical example we may further quote Heaviside's contributions to the circuit theory which is based on the notion of the sudden and discontinuous application of the "unit e.m.f." being zero before, and unity after, $t = 0$.

The great simplification which is thus occasionally obtained by considering a phenomenon to be discontinuous which in reality is continuous, appears from the example already quoted. For, if the conditions stated are fulfilled, i.e. if the application of the e.m.f. occurs in a time short in comparison with the characteristic periods and relaxation times of the system, the exact law according to which the further constant e.m.f. is applied to the circuit is immaterial as regards the resulting currents. As further examples we may quote the ballistic galvanometer, the use of the Grassot fluxmeter, etc., where only the total integral or impulse completely determines the resulting deflection, and where it is not of importance to know, for example, the exact law according to which the search coil of the fluxmeter is brought into or removed from the magnetic field to be measured.

But, apart from the simplifications mentioned, in theoretical questions or actual physical problems we occasionally encounter phenomena which may be much more easily understood if we consider them as discontinuous or discrete phenomena rather than as fully continuous. This is the case even with questions relating to the theory of the potential and waves on wires, as I intend to show later on.

Further, in considering some aspects of discontinuous phenomena, a theoretical treatment will show that relations exist between different phenomena which at

first sight seem utterly disconnected. Thus a deeper knowledge of, or better insight into, one question may, as I hope to prove, teach us much about other problems.

### (2) DISCONTINUITIES IN TIME AND SPACE

The discontinuous problems which we shall consider may be divided into two groups:

(*a*) Phenomena discontinuous in time, and

(*b*) Phenomena discontinuous in space;

and, without going into too many theoretical details, we shall first treat some of those in the first category.

### (3) SHOT EFFECT

A phenomenon with which the modern radio research worker is often confronted, and which is typically discontinuous in the sense as defined above, is the shot effect. This very important physical property of all radio valves was, like many other now well-known radio phenomena, predicted by theory. Schottky announced it in 1918 by purely theoretical reasoning, and he not only predicted qualitatively its existence but even gave quantitatively its exact amount, so that later on it became one of the most accurate methods of measuring the charge of the electron. As is well known, the shot effect is caused by the fact that, say, in a saturated diode the electricity does not flow from the cathode to the anode as an infinitely divisible fluid, but as a flight of discrete particles, the electrons. Each electron reaches the anode and, if an oscillatory circuit is inserted between the anode and cathode, " impulses " this circuit. The irregular succession of impulses by all the electrons flying between the cathode and anode causes a certain more or less irregular voltage to be set up at the oscillatory circuit, constituting what is often called a " noise." On this hypothesis, and knowing the charge of the electron $e = 1 \cdot 591 \times 10^{-19}$ coulomb, the mean square of this voltage fluctuation may be calculated and is found to agree with experiment. Now it is natural to ask why the electrons do not " impulse " the circuit at the moment they leave the cathode. The answer is given by the following experiment. Imagine two vertical parallel insulated and uncharged plates A and B (representing cathode and anode of the diode) to be externally connected through a galvanometer. The motion of an electron from cathode to anode may then be imitated by moving a charged sphere from the immediate neighbourhood of the cathode plate to the immediate neighbourhood of the anode plate, during which process the galvanometer will show a deflection. If we move the charge with a constant speed, the current in the galvanometer will be constant all the time and will show *no* impulse at the moment our charged sphere touches the anode.* On the one hand, therefore, if we move the charged sphere with constant speed the current in the galvanometer circuit will be as in Fig. 1(*a*); on the other hand, in the actual case of the saturated diode, the electron does not travel with constant speed but is uniformly accelerated, and then the time function of the current is as shown in Fig. 1(*b*). However, the total current impulse, which is represented by the shaded area in Figs. 1 (*a*) and (*b*), is only of importance when we wish to study its effect on the oscillatory circuit, i.e. as long as the time of flight of the electron is short in comparison with the natural period of the oscillatory circuit, and in these circumstances the phenomenon may be considered to be a discontinuous one, the impulse being given to the oscillatory circuit during the whole period

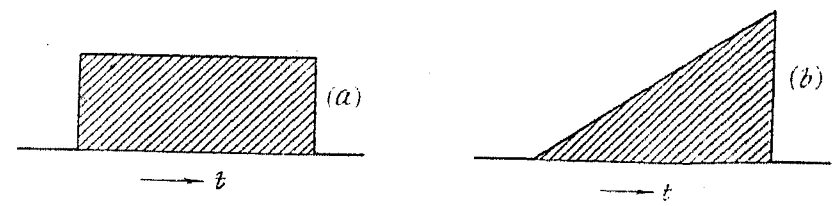


**Fig. 1.**—The current in a circuit (as a function of the time) connecting two parallel plates between which a charge is moved (*a*) with constant speed, and (*b*) with uniform acceleration.

of its flight, and not only at the moment it reaches the anode.

It therefore follows that the anode current in the diode consists of a series of irregularly spaced impulses, although for a current of $1 \cdot 591$ mA, there being $10^{16}$ of these impulses per second, it will be clear that these impulses will overlap to a great extent for voltages of the order of 100 volts, the duration of each being of the order of $10^{-9}$ sec. Hence the current will have the form shown in Fig. 2. This actual overlapping, however, is of no consequence when we wish to calculate the effect of these current impulses on an external linear circuit, because the law of superposition is then valid and the effect of each current impulse is independent of the presence of all the others.

Returning to the experiment described where we imitated the electron by moving a charged sphere between two parallel plates, it may be of interest to consider to what voltage our sphere, considered at first to be free in space, should be charged in order that it may carry the same charge as the actual electron. A simple calculation then shows that if our sphere has a diameter of 3 mm. it need only be charged to 1 $\mu$V in order to give it the charge of one electron, i.e. (notwithstanding examination papers) it is impossible to charge a sphere of 3 mm. diameter to a lower potential than 1 $\mu$V, for then it contains one electron only.

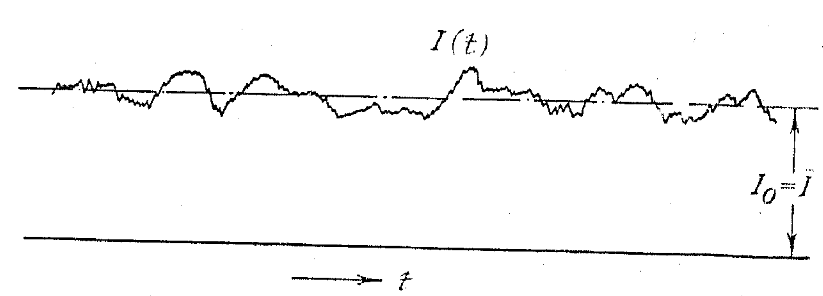


**Fig. 2.**—Schematic representation of the shot effect, with a definition of the average current $\bar{I} = I_0$.

Considering again the shot effect, which is shown in Fig. 2, we can define the average current $I_0$ as measured by a very slow-acting d.c. milliammeter. The total current can then be represented by

$$I(t) = I_0 + i(t),$$

where $i(t)$ represents the fluctuation round the average value. Now the square of this irregular current fluctua-

* See C. J. Bakker and G. De Vries: *Physica*, 1934, vol. 1, p. 1045.

tion may be considered to be analysed in a Fourier integral (we shall not consider convergence here), giving its frequency spectrum, and it can be shown from the mean of many experiments that the average contribution $d\overline{i^2}$ of its components between the frequencies $f$ and $(f + df)$ is given by

$$d\overline{i^2} = 2eI_0 \, . \, df \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $e$ is the charge of the electron and $I_0$ the mean anode current.

This expression enables us to calculate the square of the voltage fluctuation occurring over any impedance inserted in the anode circuit (see Fig. 3), at any rate as long as the direct voltage component at the anode is large enough to keep the diode saturated all the time, for then the contribution $d\overline{v^2}$ of the components between $f$ and $(f + df)$ becomes

$$d\overline{v^2} = 2eI_0|Z(j\omega)|^2 df \quad . \quad . \quad . \quad . \quad (1a)$$

The case here is a little different from those normally considered, where an e.m.f. is given and a current is to be determined. Here the current is given once for all

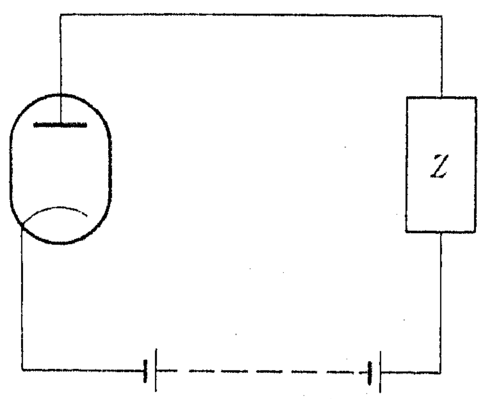


**Fig. 3.**—Saturated diode with an impedance load $Z$.

and we can calculate the resulting voltage across an impedance. Although it may be considered to be somewhat unusual to have a current given instead of an e.m.f., this makes no fundamental difference, as in general circuit theory there is a complete analogy between current and voltage.

Many investigations have now been published of the resulting voltage across an impedance, but only for a certain frequency band corresponding to the band passed by the amplifier used; but it is also of interest to investigate the total mean-square voltage fluctuation over the complete frequency spectrum to be expected in some simple cases. First I would state that, if we insert an ohmic resistance $R$ (Fig. 4$a$), the total resulting voltage fluctuation $\overline{v^2}$, from (1), will be

$$\overline{v^2} = \int_0^\infty 2eI_0R^2 df = 2eI_0R^2 \int_0^\infty df$$

and this expression diverges. Hence the simple theory considered leads to erroneous results, apart from the fact that, as we saw before, it may not be used for frequencies the period of which is of the order of the time of flight of the electrons in the diode. But we at once obtain a convergent integral if, as in Fig. 4($b$), we shunt the resistance by a capacitance $C$. For now the square of the modulus of the impedance which has to be used instead of $R^2$ is

$$\frac{R^2}{1 + (\omega CR)^2}$$

and our integral becomes

$$\overline{v^2} = 2eI_0 \int_0^\infty \frac{R^2 df}{1 + (2\pi fCR)^2} = \frac{eI_0R}{2C}$$

Remembering further that the momentary voltage $V(t)$ over the impedance is given by

$$V(t) = V_0 + v(t)$$

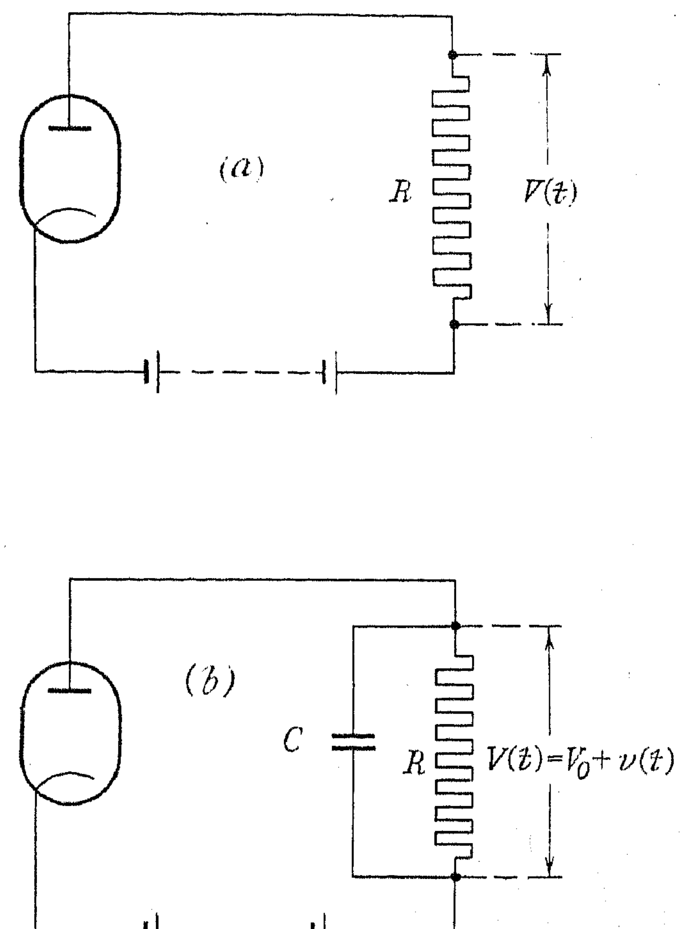


**Fig. 4.**—Saturated diode with ($a$) a resistance load $R$, and ($b$) a resistance load $R$ shunted by a capacitance $C$.

where $V_0 = \overline{V(t)}$ is the mean voltage, we have

$$\overline{v^2} = \frac{eI_0R}{2C} = \frac{1}{2} \cdot \frac{eV_0^2}{CV_0} = \frac{1}{2} \cdot \frac{eV_0^2}{Q_0}$$

where $Q_0$ represents the mean charge on the condenser, this being equal to $N_0e$, $N_0$ being the number of electrons on the condenser, and hence we obtain the very simple relation

$$N_0 = \frac{1}{2} \cdot \frac{V_0^2}{\overline{v^2}} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This means that the number $N_0$ of the electrons on the condenser equals half the ratio of the square of the direct voltage and the mean square of the voltage fluctuation over the condenser, *the magnitude of both the resistance and the capacitance having disappeared.*

When the diode is not operated under saturation

conditions, much more complicated phenomena intervene which, as far as I am aware, have not yet been completely investigated and solved.

## (4) "CIRCUIT NOISE," OR BROWNIAN MOTION

Closely related to, although distinct from, the shot effect, is the phenomenon of spontaneous current and voltage fluctuations in a passive circuit. These are due to the interchange of kinetic energy between molecules and electrons under the action of heat motion. This phenomenon, often wrongly referred to by the term "circuit noise," is nothing other than the Brownian motion of the electrons. The phenomenon was first observed with material particles in 1828 by the English botanist Brown, who put pollen from living plants on water and saw it moving in an irregular way. Thinking for a time that he was confronted with life itself, he repeated the experiment with pollen from plants which had been in a herbarium for 100 years. He observed the same motion. Thereupon he tried the experiment with granite dust from an Egyptian sphinx, with the same result.

The quantitative theory of this Brownian motion was given by A. Einstein (1906),* H. A. Lorentz (1912),† and the latter's daughter Mrs. G. L. de Haas-Lorentz (1912).‡ These investigators applied their theoretical deductions not only to material particles but also to electrical circuits. They predicted that the spontaneous mean square voltage fluctuation $\overline{v^2}$ over a condenser would be given by the expression

$$\tfrac{1}{2}C\overline{v^2} = \tfrac{1}{2}kT \quad \text{. . . . . . (3)}$$

where $T$ is the absolute temperature of the condenser and $k$ Boltzmann's constant, which is

$1\cdot37 \times 10^{-16}$ erg per degree,
$= 3\cdot81 \times 10^{-23}$ joule per degree,
$= 0\cdot86 \times 10^{-4}$ electron volt per degree.

These thermal fluctuations, which were later fully confirmed by experiment and which play an important role in the modern design of radio apparatus, therefore constitute another important radio phenomenon which was fully predicted by theoretical considerations.

Just as in the case of the shot effect, the square of the thermal fluctuations of either the voltage $v$ or the current $i$ in a circuit (Fig. 5) may be considered to be analysed by a Fourier integral, and the contributions $d\overline{v^2}$ and $d\overline{i^2}$ to the total voltage or current fluctuations for the frequency range $f$ and $(f + df)$ are given by

$$d\overline{v^2} = 4kT \,.\, Re\left[Z(j\omega)\right] . \,df \quad \text{. . . (4a)}$$

$$d\overline{i^2} = 4kT \,.\, Re\left[A(j\omega)\right] . \,df \quad \text{. . . (4b)}$$

where $Z(j\omega)$ and $A(j\omega)$ represent the complex impedance and admittance of the circuit and $Re$ [ ] means that only the real part has to be considered. Further, as usual, $\omega = 2\pi f$.

Again, as in the case of the shot effect, many investigations have been published, calculating or measuring the contribution to $\overline{v^2}$ or $\overline{i^2}$ for a finite frequency range (the band passed by an amplifier), but here again it is of interest to consider for a moment the complete spectrum.

Referring to Fig. 6($a$), let us first consider again the simplest case of a pure ohmic resistance $R$, and calculate the mean-square voltage fluctuation over the whole spectrum $f = 0$ to $f = \infty$. Applying eqn. 4($a$), we obtain

$$\overline{v^2} = 4kT\int_0^\infty R\,df = 4kTR\int_0^\infty df$$

and, just as in the case considered with respect to the shot effect, it is seen that again our integral diverges. As in that case, we can here again obtain convergence if we shunt the resistance $R$ by a capacitance $C$ (Fig. 6$b$), for then the real part of the impedance becomes $R/[1 + (\omega CR)^2]$ and, applying eqn. 4($a$), we obtain

$$\overline{v^2} = 4kT\int_0^\infty \frac{R\,df}{1 + (\omega CR)^2} = \frac{kT}{C}$$

or

$$\tfrac{1}{2}C\overline{v^2} = \tfrac{1}{2}kT$$

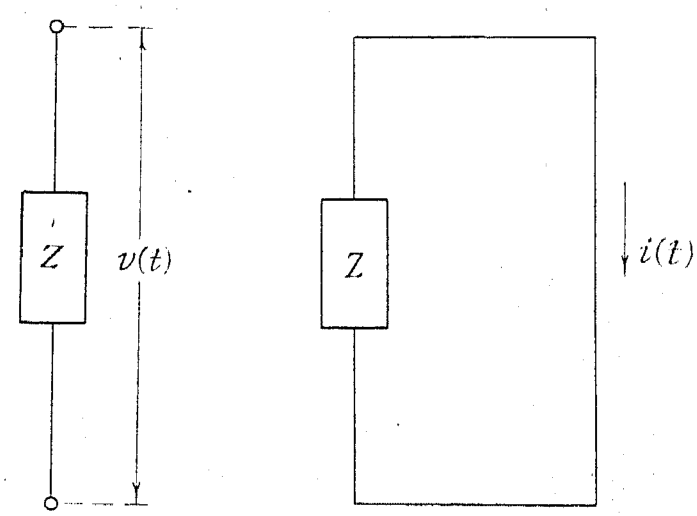


**Fig. 5.**—The spontaneous voltage fluctuation $v(t)$ over an impedance $Z$, and the spontaneous current fluctuation $i(t)$ in a circuit closing the impedance $Z$.

which is the value (see eqn. 3) predicted by Einstein, Lorentz, and De Haas-Lorentz. It is of great interest to note that the magnitude of the resistance does not appear in the result. But we can extend our result and apply eqn. 4($a$) to the more complicated case of Fig. 6($c$), where we have further shunted the system with an inductance $L$. Now $Z(j\omega)$ becomes

$$Z(j\omega) = \frac{R}{1 + R\left(j\omega C + \dfrac{1}{j\omega L}\right)}$$

and

$$Re\left[Z(j\omega)\right] = \frac{R}{1 + R^2\left(\omega C - \dfrac{1}{\omega L}\right)^2}$$

so that we obtain for the mean-square voltage fluctuation $\overline{v^2}$

$$\overline{v^2} = 4kT\,.\int_0^\infty \frac{R\,df}{1 + R^2\left(\omega C - \dfrac{1}{\omega L}\right)^2} = \frac{kT}{C}$$

* *Annalen der Physik*, 1906, vol. 19, p. 371.
† "Les Théories Statistiques en Thermodynamique" (Leipzig, 1916).
‡ "Die Brownsche Bewegung" (Braunschweig, 1913).

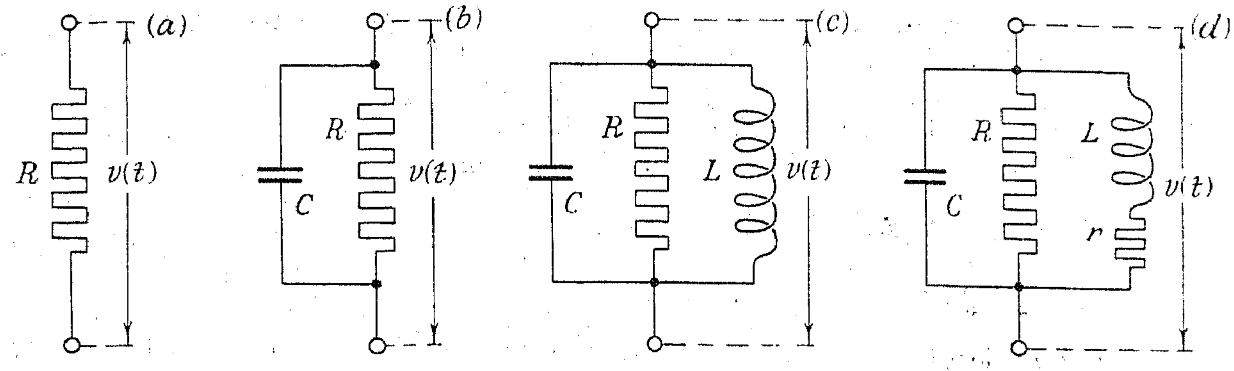


**Fig. 6.**—Considering the complete frequency spectrum, the circuit of (*a*) gives an infinite voltage fluctuation, whereas the spontaneous voltage fluctuations $\overline{v^2(t)}$ over the three different impedances in (*b*), (*c*), and (*d*), are finite and equal.

which is the result already found, although the integral has a totally different form. But we can still further complicate the circuit and insert a resistance $r$ in series with the inductance Fig. 6($d$), calculate the real part of the impedance thus obtained, and integrate over all frequencies. Once again we obtain the same result, which appears to be independent of the values of the three circuit elements $R$, $L$, and $r$, only $C$ entering into the result. A further investigation of these properties of circuits will be published elsewhere.

### (5) THE IMPULSIVE FUNCTION

In the Introduction and also subsequently, I had occasion to remark that many phenomena, in which a parameter was suddenly varied during a time which was short compared with the shortest relaxation time or period of the circuit, do not depend on the exact manner in which this parameter is changed, but only on the time integral of the variation of this parameter, i.e. its total impulse or moment. In order to ensure that, for example, an applied e.m.f. always fulfils this condition, this e.m.f. must be made to last only an infinitesimal time, but in order to keep its integral finite (say unity) it must in the course of this infinitesimal time reach infinity in magnitude. We are thus lead to the "impulsive function" $\delta(t)$, which is schematically represented in Fig. 7 and which can be considered to be the limit of several functions, such as

$$\delta(t) = \operatorname*{Lim.}_{\alpha\to\infty} \sqrt{\frac{\alpha}{\pi}}\,.\,e^{-\alpha t^2} \quad . \quad . \quad . \quad . \quad . \quad (5a)$$

$$\delta(t) = \operatorname*{Lim.}_{\alpha\to\infty} \frac{\alpha}{2} e^{-\alpha|t|} \quad . \quad . \quad . \quad . \quad . \quad (5b)$$

$$\delta(t) = \operatorname*{Lim.}_{\alpha\to+0} \frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{-\alpha|\omega|}\cos\omega t\,.\,d\omega \quad . \quad . \quad (5c)$$

or

$$\delta(t) = \operatorname*{Lim.}_{\alpha\to+0} \frac{1}{\pi}\,.\,\frac{\alpha}{\alpha^2+t^2} \quad . \quad . \quad . \quad . \quad . \quad (5d)$$

It is this function $\delta(t)$ that is extensively used by Dirac in his atomic theory, and by Heaviside in his operational calculus, but one of the first well-defined applications of this function to physical phenomena is to be found in a paper by Kirchhoff,* where he defines his function as in eqn. (5*a*), and in a paper by Von Helmholtz,† who used (5*d*).‡ In abstract mathematical literature the use of this function is usually avoided, it being replaced by its (discontinuous) time integral, thus exhibiting a discontinuous behaviour such as is the case in many integrals containing a parameter, the integral representing, for example, a different value according to whether the parameter is positive or negative.

As a tool for heuristic purposes this $\delta(t)$ function is of great value in physical applications. It is sufficient for our purpose to define it as a function which is zero everywhere except in the immediate neighbourhood of $t = 0$, where it becomes infinite in such a way that its

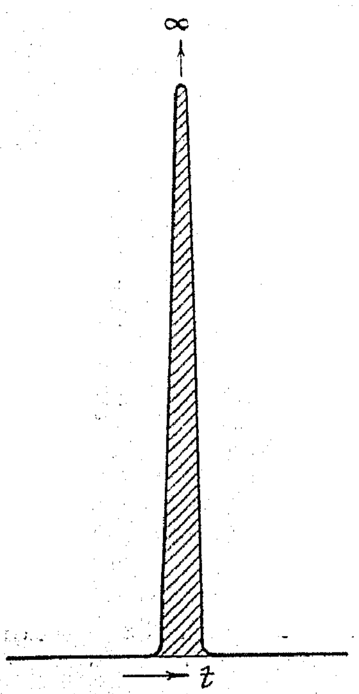


**Fig. 7.**—Schematic representation of the impulsive function $\delta(t)$.

time integral or total moment is unity. It thus only "lasts" for a time which is short compared with the shortest natural period of the system under consideration. It has the dimension $T^{-1}$, and this fact should be borne in mind in considering some of the formulae of the present lecture from the point of view of dimensions.

### (6) THE APPLICATION OF THE IMPULSIVE FUNCTION TO THE CALCULATION OF THERMAL FLUCTUATIONS

After this introduction of the impulsive function $\delta(t)$ we are now ready to apply it in order to find the total (including all frequencies) mean-square thermal voltage fluctation $\overline{v^2}$ between any two terminals A and B of a circuit. To this end we imagine an impulsive e.m.f. of magnitude $\sqrt{(2r_n kT_n)}\,.\,\delta(t)$ to be inserted in series with

* G. Kirchhoff: "Vorlesungen über Mathematische Optik," 1891, p. 24.
† H. von Helmholtz: "Vorlesungen über die Elektromagnetische Theorie des Lichtes."
‡ See also W. E. Sumpner: *Philosophical Magazine*, 1931, vol. 11, p. 345.

each resistance in turn. We first consider this impulsive voltage to be present only in the resistance $r_1$ and having therefore the magnitude $\sqrt{(2r_1kT_1)}\,.\,\delta(t)$, $T_1$ being the temperature of the resistance $r_1$. Let this e.m.f. cause a potential difference $v_1(t)$ between the terminals A and B. Next, calculate the time integral $\int_0^\infty v_1^2(t)dt$. If we imagine an e.m.f. of magnitude $\sqrt{(2r_2kT_2)}\,.\,\delta(t)$ to be inserted in series with the resistance $r_2$, leading to $\int_0^\infty v_2^2(t)dt$, etc., it can be proved that the total mean-square thermal voltage fluctuation $\overline{v^2}$ between the points A and B is then given by

$$\overline{v^2} = \int_0^\infty (v_1^2 + v_2^2 + \ldots v_n^2)dt \quad . \quad . \quad . \quad (6)$$

*Example.*

Consider the circuit of Fig. 8, in which there is only one resistance $r$ present in the system. Imagine, as depicted in the figure, an e.m.f. of magnitude $\sqrt{(2rkT)}\,.\,\delta(t)$ to be inserted in series with the resistance $r$. This will cause a voltage $v(t)$ between the terminals A and B which is easily calculated to be

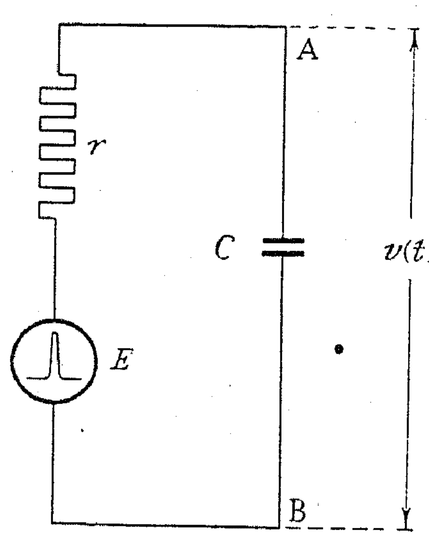


**Fig. 8.**—The spontaneous voltage fluctuation derived from the response $v(t)$ due to an impulsive excitation $\delta(t)$.

$$v(t) = \sqrt{(2rkT)}\,\frac{1}{Cr}\,e^{-\frac{t}{Cr}}$$

and therefore the total mean-square thermal voltage fluctuation $\overline{v^2}$ between the points A and B is given by

$$\overline{v^2} = \int_0^\infty v^2 dt = 2rkT\,\frac{1}{C^2r^2}\int_0^\infty e^{-\frac{2t}{Cr}}dt = \frac{kT}{C}$$

which again gives the result

$$\tfrac{1}{2}C\overline{v^2} = \tfrac{1}{2}kT.$$

## (7) APPLICATION OF THE IMPULSIVE FUNCTION TO GENERAL CIRCUIT THEORY

It is customary in radio and line technique to determine the behaviour of a circuit under any arbitrary voltage form from a knowledge of its behaviour under sinusoidal impressed voltages. Obviously this method is based on Fourier's integral, for we can imagine the arbitrary voltage to be decomposed into its Fourier components, and, if the response of the circuit is known to each of these components, the individual responses can be added to give the complete response.

This method is correct in itself, as it may be assumed that all electromotive forces occurring in practice fulfil the conditions for a function to be developable into a Fourier integral. However, although a complete knowledge of the response of a system under impressed sinusoidal forces of all frequencies enables us to predict its response under any arbitrary force, it does not tell us the exact constitution of the circuit. This may be exemplified with the aid of Fig. 9, where four different circuits are given which all respond as a pure resistance $r$. In the first case the box contains a pure resistance $r$ only, in the second case we have an infinite line for which $\sqrt{(L/C)} = r$, in the third case a finite line is terminated with a resistance $r$ equal to the characteristic impedance $\sqrt{(L/C)}$, and in the fourth case we have a $L$, $C$, $r$, $r$ circuit which also behaves as a pure resistance $r$ for all frequencies.

As long as we are concerned with responses in the audio-frequency spectrum, the phases of the individual responses are not of prime importance since, as a first approximation, the ear may be regarded as insensitive to small phase-differences. In television technique, however, matters are quite different, as it will be obvious that true reproduction of the phases is there of prime importance.

Now it has been shown by, among others, Carson, Lee, and Bayard,* that "the behaviour of a network under all circumstances is completely determined if either the real or imaginary component of the complex steady-state admittance is specified over the entire frequency range," and the same may be said for the complex steady-state impedance, for a knowledge of the real part of an impedance enables us to calculate its imaginary part, and vice versa, so that either is sufficient. In the Appendix the general transformation formulae are given.

From what has been said it follows that a knowledge of one function of $\omega$ only (either the real or the imaginary part of the impedance) is sufficient to determine the behaviour of the system under any impressed voltage.

Now it is of great interest that there is another, or even many other, methods of determining this general behaviour. The one to which I would draw special attention, and which has proved to be of great practical utility, is the following: *If we know the response of a passive network to an impulsive voltage, we can always determine its response to any other arbitrary voltage.* For, if the response of a circuit to a voltage $\delta(t)$ is represented by $i^*(t)$, the response $i(t)$ to a voltage $E(t)$ can immediately be obtained in the form

$$i(t) = \int_{-\infty}^{+\infty} E(t-\tau)i^*(\tau)d\tau,$$

* J. R. CARSON: "Electric Circuit Theory and Operational Calculus," p. 180 (New York, 1926). Y. W. LEE: *Journal of Mathematics and Physics*, 1932, vol. 11, p. 83. M. BAYARD: *Revue Générale de l'Electricité*, 1935, vol. 37, p. 659.

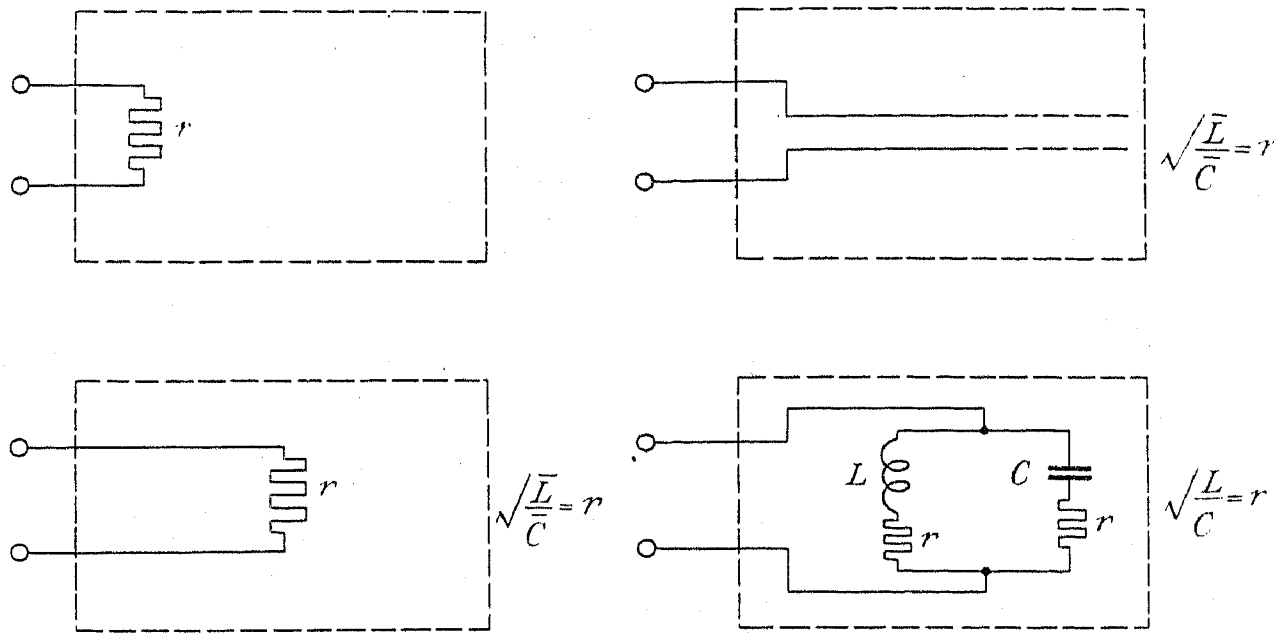


**Fig. 9.**—Four different impedances which for all frequencies behave as a resistance $r$.

and hence the problem is solved by one single integration only.

Moreover, there exists a close relation between this response $i^*(t)$ to an impulsive voltage and the usual steady-state complex admittance $A(j\omega)$ or its reciprocal, the impedance $Z(j\omega)$. For the complex admittance is simply the complex Fourier transform of $i^*(t)$, or

$$A(j\omega) = \frac{1}{Z(j\omega)} = \int_{-\infty}^{+\infty} e^{-j\omega t}\, i^*(t)dt \quad . \quad . \quad (7a)$$

and hence also the response $i^*(t)$ is in its turn the complex Fourier transform of the admittance, viz.

$$i^*(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{+j\omega t} A(j\omega)d\omega \quad . \quad . \quad . \quad (7b)$$

The relations ($7a$) and ($7b$) are valid for passive, dissipative networks, and it is assumed that the integral exists.

Hence, as in the case of the complex impedance, where a knowledge of one function of $\omega$ only (either the real or imaginary part over the whole frequency range) was sufficient to determine the general behaviour of the network, so also here a knowledge of one function $i^*(t)$, but in this case of time, completely suffices.

## (8) THE BEHAVIOUR OF A LOW-PASS FILTER UNDER AN IMPULSIVE VOLTAGE, AND THE TRANSITION TO A SMOOTH LINE

So far we have considered in a summary way some effects related to discontinuities in *time*, and I propose now to consider some questions related to discontinuities in *space*. The first problem is the transient behaviour of a low-pass filter. A low-pass filter can be considered as a degeneration of a smooth line, where the $L$'s and $C$'s, instead of being homogeneously distributed along a space co-ordinate as in a smooth line, are concentrated in a discontinuous way at equal spacial distances.

As our treatment of this low-pass filter differs from the usual one, in so far as it is based on the properties of a *difference equation*, a short introduction on *finite differences* may not be out of place, the more so as our basic definition of a finite difference differs somewhat from the one usually given in the mathematical textbooks on the subject.*

For reasons which will be clear later in the paper, the symmetrical finite difference with unity steps of a function $F_n$ is defined as

$$\Delta_n F_n = F_{n+\frac{1}{2}} - F_{n-\frac{1}{2}} \quad . \quad . \quad . \quad (8)$$

which definition is further illustrated in Fig. 10. From

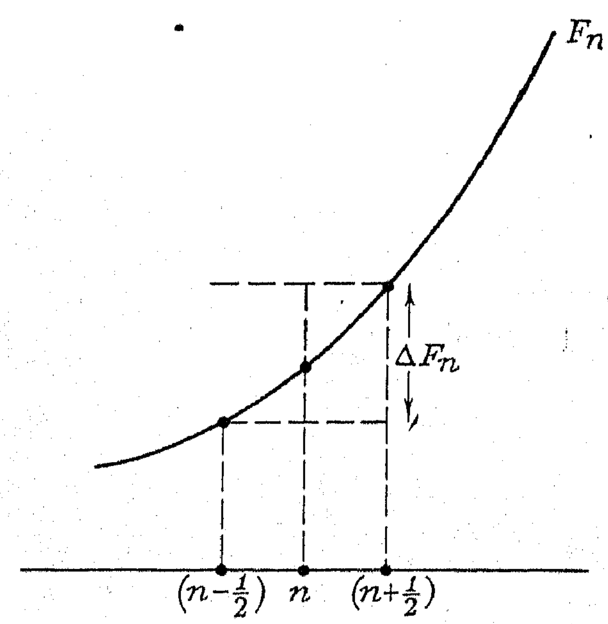


**Fig. 10.**—Definition of the first-order symmetrical finite difference $\Delta F_n$ of a function $F_n$.

the definition (8) we at once obtain the expression for $\Delta_n^2 F_n$ as

$$\begin{aligned}\Delta_n^2 F_n &= (F_{n+1} - F_n) - (F_n - F_{n-1}) \\ &= F_{n+1} - 2F_n + F_{n-1} \quad . \quad . \quad . \quad (9)\end{aligned}$$

The geometrical meaning of which will also be clear from Fig. 11.

From these definitions it follows that a knowledge of the function $F_n$ for the values of $n = \ldots n_0 - 2$, $n_0 - 1, n_0, n_0 + 1, \ldots$ suffices to determine the values

* For instance N. E. Nörlund, "Differenzenrechnung" (Berlin, 1924), and L. M. Milne-Thomson: "The Calculus of Finite Differences" (London, 1933).

$\Delta_n^2 F_n$ in those points, but that this knowledge does not enable us to calculate the values of $\Delta_n F_n$ at those points. This drawback is, I think, at least for our purpose, more than counterbalanced by the advantages gained through the symmetry of the definition (8).

Let us now consider the low-pass filter, using the

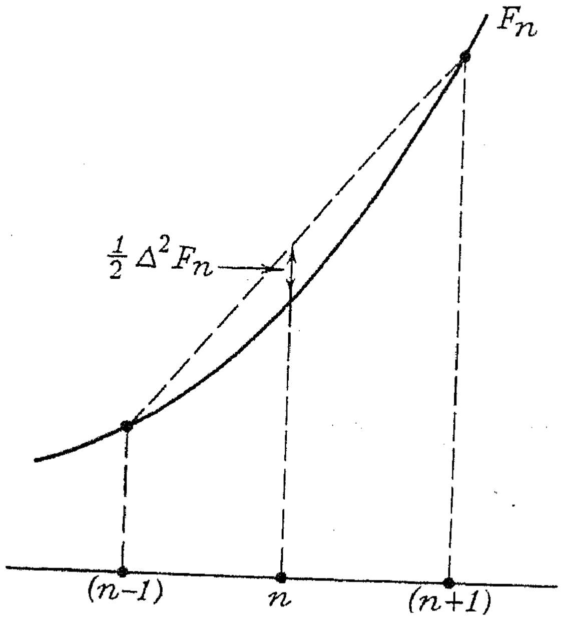


**Fig. 11.**—Definition of the second-order symmetrical finite difference $\Delta^2 F_n$ of a function $F_n$.

notations of Fig. 12. Applying the second Kirchhoff law to the mesh $n$, we obtain

$$\frac{1}{CD_t}(i_n - i_{n-1}) + LD_t i_n + \frac{1}{CD_t}(i_n - i_{n+1}) = 0$$

which, with our definition (8), can be written in the elegant way

$$\{\Delta_n^2 - CL \,.\, D_t^2\} i_n(t) = 0 \quad . \quad . \quad . \quad (10)$$

so that, concentrating our attention on $V_n(t)$, (10$a$) becomes

$$\left(\sinh^2 \tfrac{1}{2}D_n - \frac{1}{\omega_0^2}D_t^2\right) V_n(t) = 0$$

or, replacing $D_t$ operationally by $p$, $\left[t = \frac{1}{p}\right]$, and $V_n(t)$ by $F_n(p)$,

$$\sinh^2 \tfrac{1}{2}D_n \,.\, F_n(p) = \frac{p^2}{\omega_0^2} \,.\, F_n(p).$$

Hence, operating on $F_n(p)$ with $\sinh^2 \frac{1}{2}D_n$ gives the same result as multiplication by $p^2/\omega_0^2$, and therefore

$$(\tfrac{1}{2}D_n)^2 F_n(p) = \left(\text{arc sinh}\,\frac{p}{\omega_0}\right)^2 F_n(p)$$

or, as we know from the physics of the system that we shall be concerned only with outgoing waves,

$$\tfrac{1}{2}D_n F_n(p) = -\text{ arc sinh}\left(\frac{p}{\omega_0}\right) F_n(p).$$

This is a simple differential equation for $F_n(p)$, $D_n$ denoting $\frac{d}{dn}$, the solution of which is

$$F_n(p) = \psi(p) e^{-2n \,\text{arc sinh}\, \frac{p}{\omega_0}} \quad . \quad . \quad (11)$$

where $\psi(p)$ is an arbitrary function of $p$.

As, however, our initial boundary condition is $V_n(t) = \delta(t)$ for $n = 0$, which corresponds to $F_n(p) = p$ for $n = 0$, we at once see that the function $\psi(p)$ must be $p$ [because $\delta(t) \doteqdot p$], and hence the final operational solution of our problem is

$$F_n(p) = pe^{-2n \,\text{arc sinh}\, \frac{p}{\omega_0}} \quad . \quad . \quad . \quad (12)$$

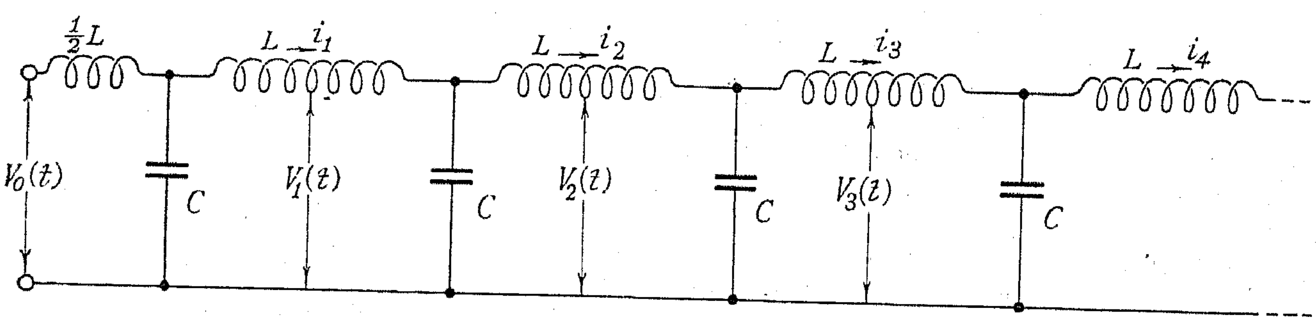


**Fig. 12.**—Low-pass filter.

It is further known that the cut-off frequency $\omega_0$ of this filter is given by $\omega_0^2 = 4/(CL)$, so that (10) becomes

$$\left(\Delta_n^2 - \frac{4}{\omega_0^2}D_t^2\right) i_n(t) = 0 \quad . \quad . \quad . \quad (10a)$$

and a similar equation is valid for the mid-section voltage $V_n(t)$ instead of $i_n(t)$.

In order, now, to obtain in a simple way $V_n(t)$ for the initial boundary condition $V_0(t) = \delta(t)$, i.e. the behaviour of the filter under an impulsive voltage applied at the beginning (the network being supposed to be at rest for $t < 0$), we replace $\Delta_n$ by

$$\Delta_n = e^{\frac{1}{2}D_n} - e^{-\frac{1}{2}D_n} = 2 \sinh \tfrac{1}{2}D_n,$$

the equivalent original of which is known,* yielding as the solution of our problem

$$V_n(t) = \frac{2n}{t} J_{2n}(\omega_0 t) \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where $J_{2n}(\omega_0 t)$ is the Bessel function of order $2n$ and argument $\omega_0 t$. These functions of the two variables $n$ and $\omega_0 t$ are represented in Fig. 13 (see Plate 1, facing page 388) (the original three-dimensional model of which was shown at the lecture). Our result (13) can also be derived from a formula given by Carson.† We therefore see that the response in the $n$th element of the

* BALTH. VAN DER POL: *Philosophical Magazine*, 1929, vol. 8, p. 861.
† J. R. CARSON: *loc. cit.*

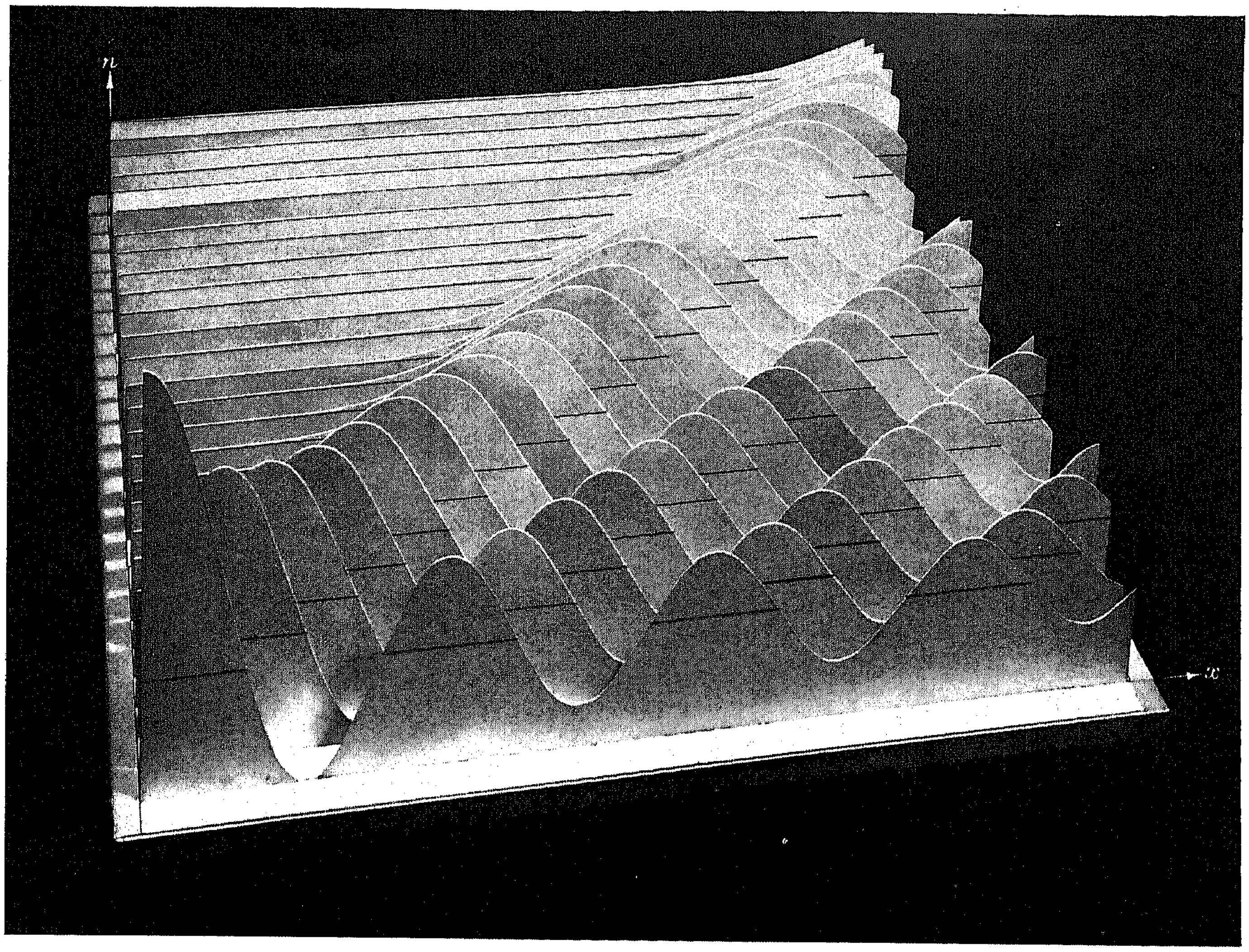


**Fig. 13.**—Model representing Bessel functions $J_n(x)$ as a function of $n$ and $x$.

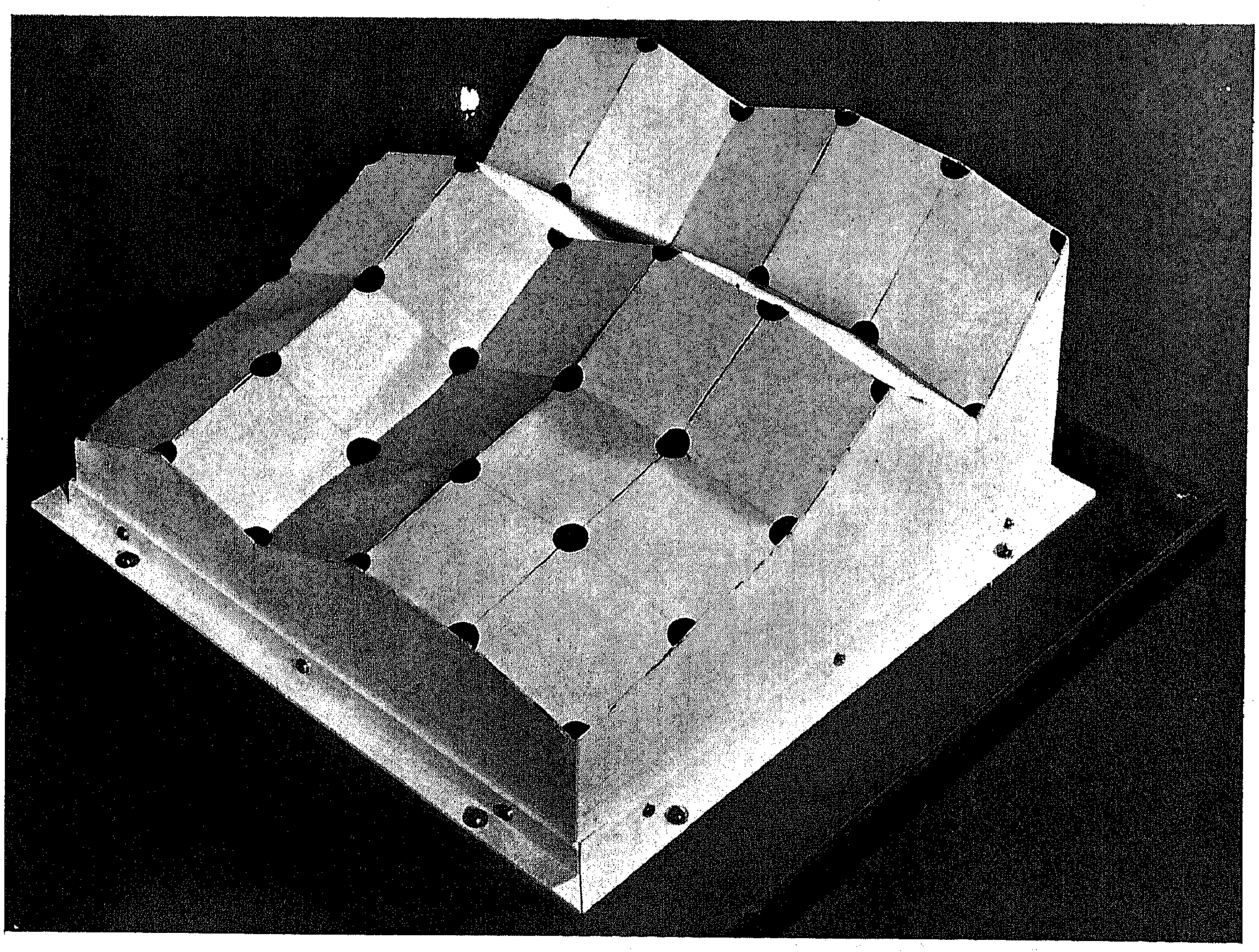

**Fig. 17.**—Three-dimensional model of the solution of the discrete wave equation represented in Fig. 16.

*Plate 2*

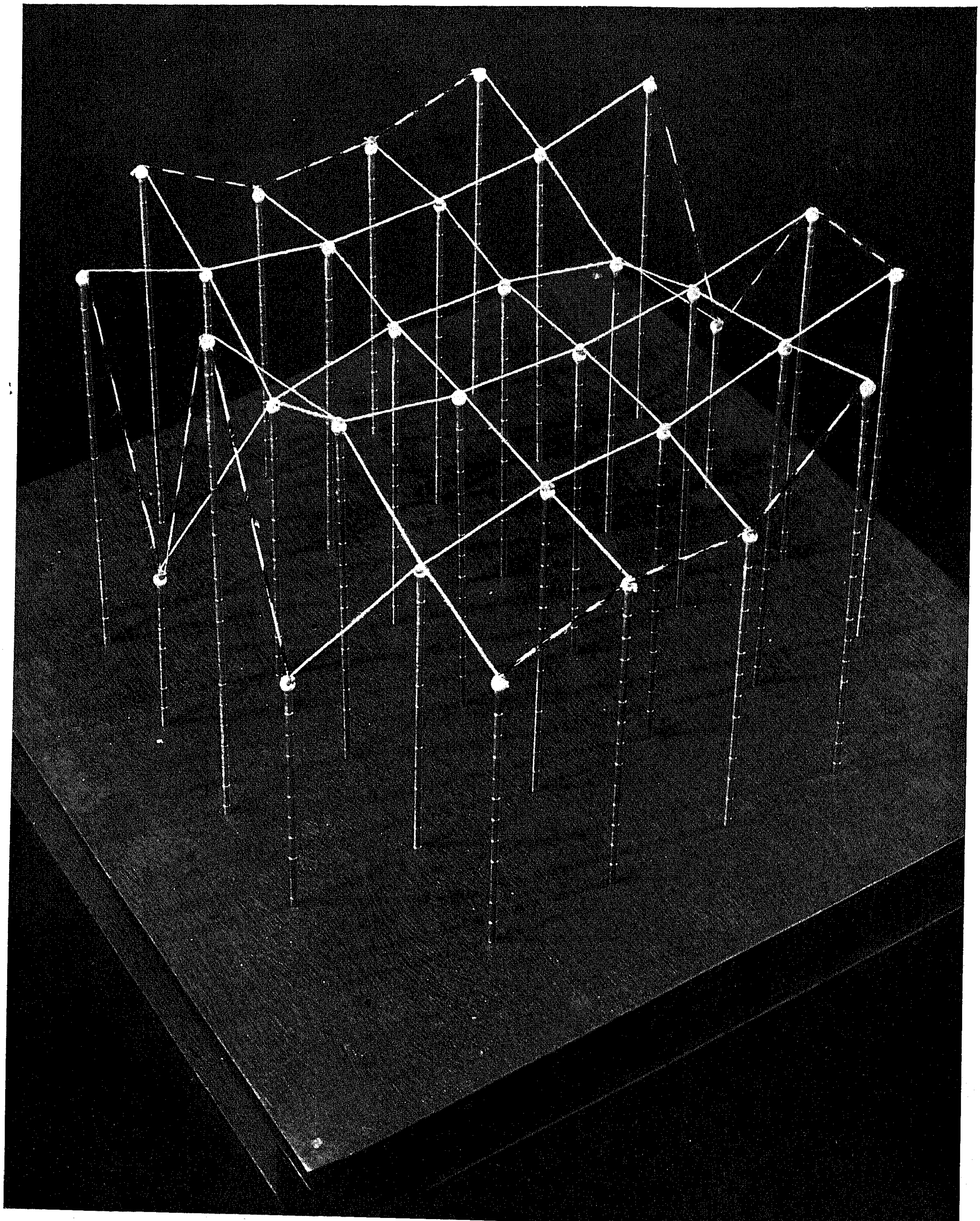

**Fig. 22.**—Three-dimensional model of a solution of the two-dimensional discrete potential equation.

If the values on the boundary are given (shown dotted in the figure) all the interior values follow as shown by the white lines. The white lines show the way in which elastic wires, stretched between the given boundary points and interwoven, would automatically place themselves.

low-pass filter under impulsive excitation at the beginning is represented by a Bessel function.

It is further of interest to note that if, instead of an impulse voltage excitation in the zero'th mesh, we had inserted the excitation

$$V_0^*(t) = \frac{m}{t} J_m(\omega_0 t)$$

$\psi(p)$ of (11) had to be taken as $pe^{-m \operatorname{arc\,sinh} \frac{p}{\omega_0}}$ instead of $p$, and the voltage response in the $n$th branch would have been operationally

$$F_n^*(p) = pe^{-(2n+m) \operatorname{arc\,sinh} \frac{p}{\omega_0}}$$

or, in terms of a function of $t$,

$$V_n^*(t) = \frac{2n+m}{t} J_{2n+m}(\omega_0 t),$$

so that the voltage response in the $n$th mesh is simply obtained by adding $2n$ to $m$ in the expression for the excitation voltage at the beginning of the filter. If, therefore, any excitation voltage $V_0(t)$ is applied at the beginning of the filter, and if this voltage can be represented by the series

$$V_0(t) = \sum_{m=0}^{m=\infty} a_m \frac{m}{t} \cdot J_m(\omega_0 t)$$

the potential difference in the $n$th mesh is at once given by

$$V_n(t) = \sum_{m=0}^{m=\infty} a_m \frac{m+2n}{t} J_{m+2n}(\omega_0 t).$$

This shows the great advantage sometimes obtained by developing the applied e.m.f. in other than Fourier series or Fourier integrals. In fact, I am of the opinion that *in communication technique the practical value of the Fourier spectral analysis seems occasionally to be over-estimated, there being many other orthogonal functions, for example* $\delta(t - t_0)$ *or Bessel functions, which could often with advantage take the place of the more common sine and cosine functions.*

Returning to the symbolic formula (12), representing the voltage response in the $n$th branch of a low-pass filter under impulse excitation at the beginning, we shall now demonstrate the transition of this low-pass filter to a smooth line. To this end, we keep the distance $l$ to the $n$th element fixed. The total self-inductance between the beginning and this element is then given by $nL = l\overline{L}$, and similarly $nC = l\overline{C}$, where $\overline{L}$ and $\overline{C}$ are the constants per unit length. We further call $\overline{LC} = 1/c^2$. Next, we divide each element of the filter into $s$ elements, so that $n' = ns$ and at the same time the cut-off frequency is increased towards $\omega_0' = \omega_0 s$. Thus the p.d. in the $n$th element becomes symbolically, according to (12),

$$F_n(p) = pe^{-2ns \operatorname{arc\,sinh} \frac{p}{\omega_0 s}}$$

and if we now take the limit of this expression for $s \to \infty$, we obtain in the limit for the smooth line

$$\lim_{s \to \infty} F_n(p) = pe^{-2ns \cdot \frac{p}{\omega_0 s}} = p\,e^{-\frac{pl}{c}},$$

representing again an impulse but retarded by the time $l/c$, or

$$\lim_{s \to \infty} V_n(t) = \delta(t - l/c)$$

as we should expect for a smooth line. At the same time the critical cut-off frequency is seen to go towards infinity, so that, contrary to what happens with a low-pass filter, now all frequencies are faithfully reproduced and there is no distortion. The great simplicity of this limiting process affected in the operational field is to be noted.

### (9) THE "DISCRETE WAVE EQUATION"

In Section (8) we saw that the low-pass filter was represented by a *difference differential* equation (10$a$), which, if we absorb a mathematically immaterial constant in the unit of time, can be written as

$$\Delta_n^2 = D_t^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Equation (14) may further be contrasted with the partial differential equation for a smooth line

$$D_x^2 = D_t^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

In this connection it is natural also to consider the partial differential equation

$$\Delta_n^2 = \Delta_m^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

representing an extension in the discreteness in time ($m$) similar to the extension in the discreteness of space, when we transformed (15) into (14).

As far as I am aware, very little is known about these partial differential equations, apart from an investigation by Courant, Friedrichs, and Lewy,* who, however, use *asymmetric* differences. I shall now endeavour to extend their work physically. In doing so I shall obtain results which, I think, may throw some further light even on such elementary questions as the theory of the potential. My development may, perhaps, be used with advantage in introducing such notions as *divergence* and *curl* to students of the elementary theory of the electric field.

For let us take (16), which may be written more fully as

$$(\Delta_n^2 - \Delta_m^2)F_{n,m} = 0 \quad . \quad . \quad . \quad . \quad . \quad (17)$$

or

$$F_{n+1,m} - 2F_{n,m} + F_{n-1,m} - F_{n,m+1} + 2F_{n,m} - F_{n,m-1} = 0,$$

or even further simplified to

$$F_{n+1,m} + F_{n-1,m} = F_{n,\,m+1} + F_{n,m-1} \quad . \quad (18)$$

Consider a two-dimensional rectangular lattice or net with co-ordinates $m$ and $n$; then the values of the function $F_{n,m}$ may be written at the corresponding points $(m, n)$. We thus obtain a diagram such as Fig. 14. In Fig. 15 the same diagram is reproduced, but only a few values such as $a, b, c, d$, this group being chosen at an arbitrary place in the whole field, have been marked. Now eqn. (18) requires only that everywhere in the field the values of the function $F_{n,m}$ must be such that $a + b = c + d$, $e + g = d + f$, etc. (see

* *Mathematische Annalen*, 1928, vol. 100, p. 32.

Fig. 15). Equation (17) or (18), which is an extension of the usual wave equation (15) for a smooth line, therefore requires everywhere a condition to be fulfilled by four adjacent points, situated relatively to each other like the points $a$, $b$, $c$, and $d$. It will be clear that the total field thus divides itself in two fields, ($a$) that containing the points $a, b, c, d, e, f, g, \ldots$ and which arbitrarily may be called the *even* field, and ($b$) the field containing the interspaced points, which may be called the *odd* field. The physical reason why the wave equation, considered as the finite difference equation (16), thus leads to two different, mutually independent, interspaced fields, has not yet been investigated. However, it is easy to see that the general solution of (17) or of the fully equivalent (18) is

$$F_{n,m} = F_1(n+m) + F_2(n-m)$$

where $F_1$ and $F_2$ are arbitrary functions of the arguments $(n+m)$ and $(n-m)$ respectively. This solution is fully equivalent to the classical expression

$$F(x, t) = F_1(x + ct) + F_2(x - ct)$$

solving the "smooth" wave equation

$$\frac{\partial^2 F}{\partial x^2} = \frac{1}{c^2} \cdot \frac{\partial^2 F}{\partial t^2}$$

| $m$ | | | | |
|---|---|---|---|---|
| $F_{5,1}$ | $F_{5,2}$ | $F_{5,3}$ | $F_{5,4}$ | $F_{5,5}$ |
| $F_{4,1}$ | $F_{4,2}$ | $F_{4,3}$ | $F_{4,4}$ | $F_{4,5}$ |
| $F_{3,1}$ | $F_{3,2}$ | $F_{3,3}$ | $F_{3,4}$ | $F_{3,5}$ |
| $F_{2,1}$ | $F_{2,2}$ | $F_{2,3}$ | $F_{2,4}$ | $F_{2,5}$ |
| $F_{1,1}$ | $F_{1,2}$ | $F_{1,3}$ | $F_{1,4}$ | $F_{1,5}$ → $n$ |

**Fig. 14.**—A part of the field $F_{m,n}$.

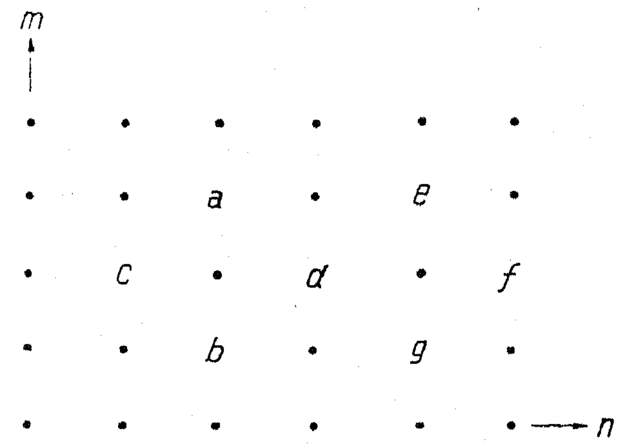


**Fig. 15.**—" Even " field, solving the discrete wave equation if $a + b = c + d$, etc.

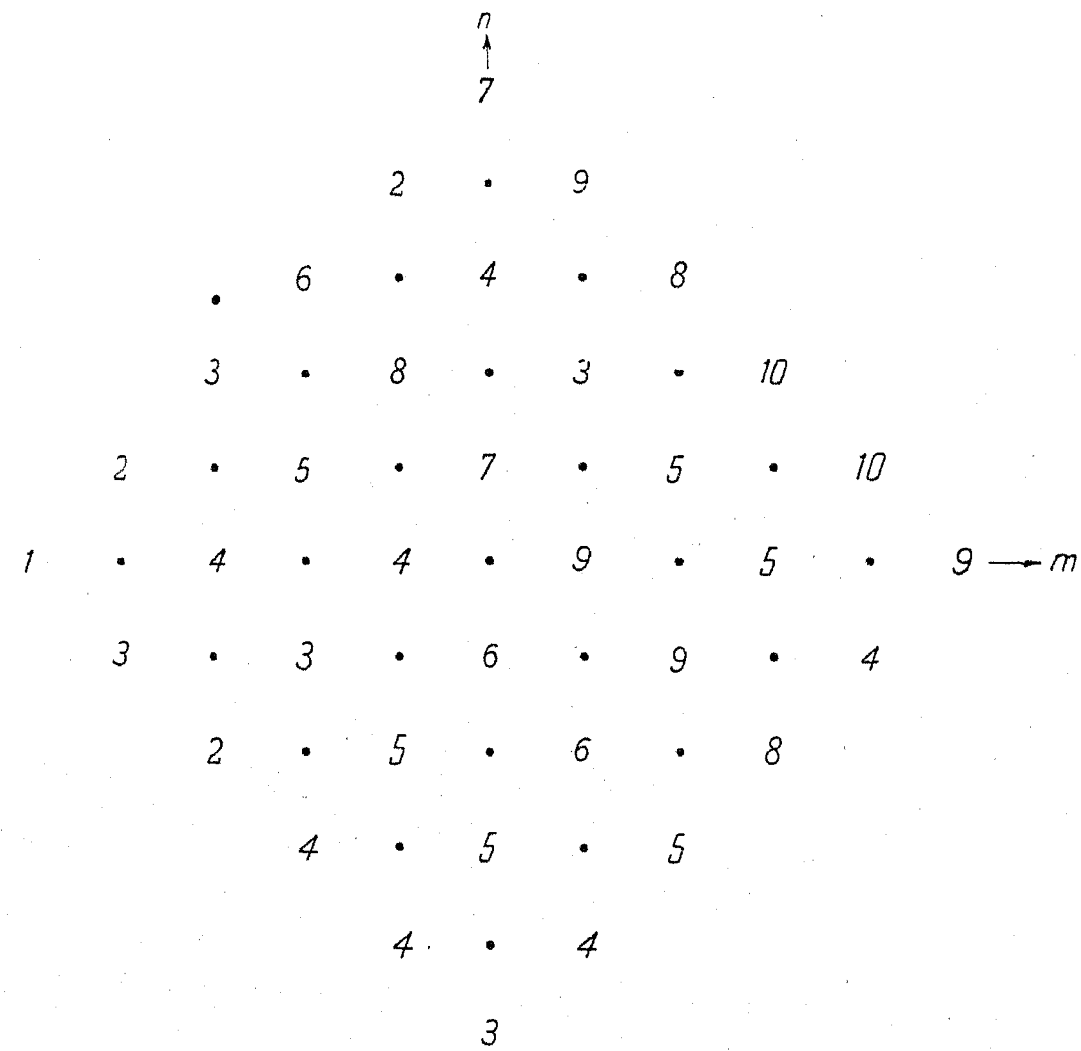


**Fig. 16.**—Example of a solution of the discrete two-dimensional wave equation.

which, apart from a different time unit, represents (15). As an example there is reproduced in Fig. 16 a special case of the function (19) in, say, the odd field, which

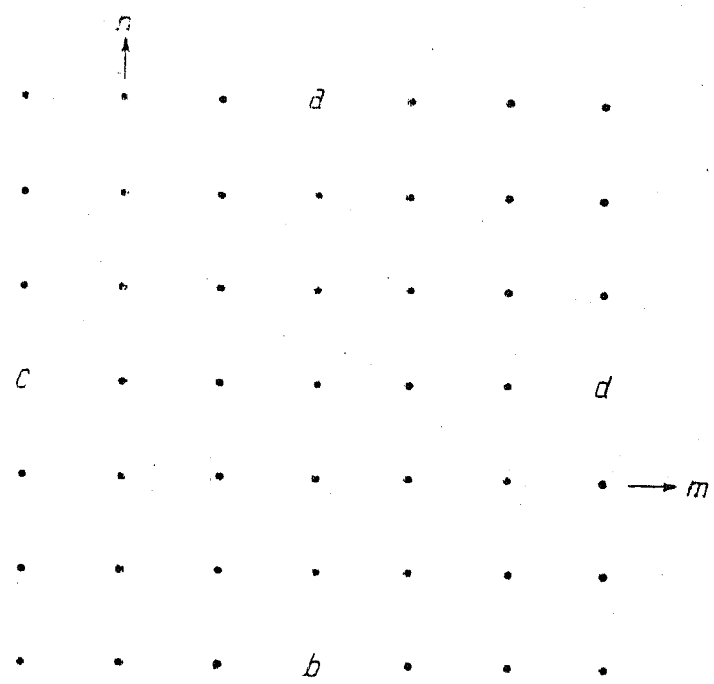


**Fig. 18.**—Any solution of the discrete wave equation has the property that $a + b = c + d$.

therefore solves the discrete wave equation (17) and a three-dimensional model, in which the heights of the points represented by the black spots correspond to the value of $F_{n,m}$ at the co-ordinates $n$ and $m$, is reproduced in Fig. 17 (see Plate 1). (The original model was shown at the lecture.) This paper model was constructed in order to show clearly that four adjacent points of either the even or the odd field always lie in a plane.

Two further elementary properties of all "wave functions" $F_{n,m}$, satisfying (17) or (18), are illustrated in Figs. 18 and 19.

(1) Four values of $F_{n,m}$ represented by $a$, $b$, $c$, and $d$, situated anywhere in the field at the four corners of a diamond-shaped figure of any size such as that shown in Fig. 18, always satisfy the condition $a + b = c + d$. The elementary condition (18), as explained by Fig. 15, in which also $a + b = c + d$, forms a special case of this general property.

(2) If we consider again a diamond-shaped part, of any size, of a wave function, situated anywhere in the field such as the points marked + and − in Fig. 19, the sum of all values of $F_{n,m}$ at the points marked + equals the sum of all values of $F_{n,m}$ marked −.

I shall not further investigate here the properties of these "wave functions."

## (10) THE "DISCRETE POTENTIAL EQUATION"

Having in Section (9) investigated some properties of the "wave functions," satisfying

$$(\Delta_n^2 - \Delta_m^2)F_{n,m} = 0 \quad . \quad . \quad . \quad . \quad (17)$$

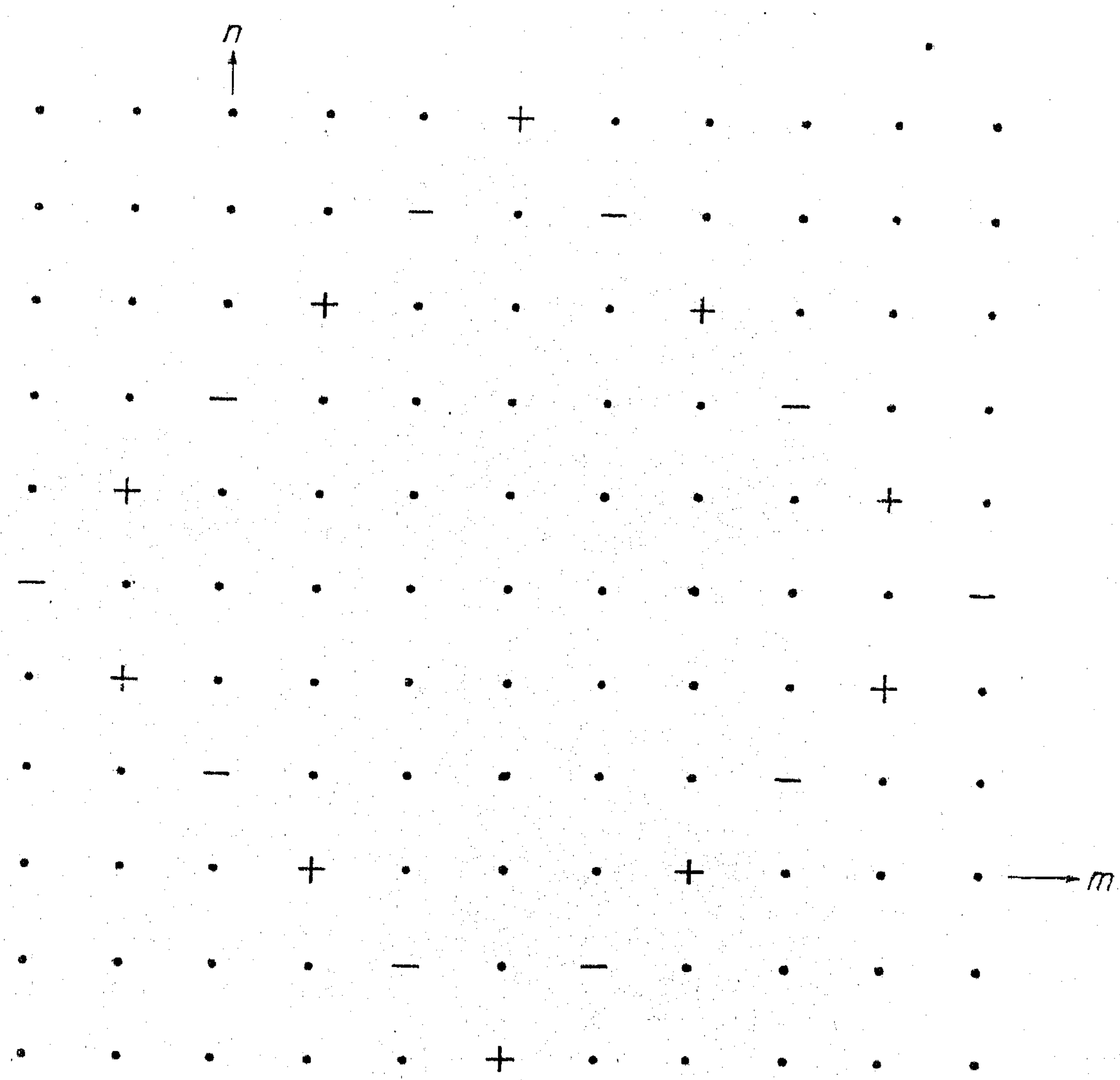


**Fig. 19.**—Any solution of the discrete wave equation has the property that the sum of the values marked + equals the sum of the values marked —.

I propose now to investigate the solutions of another *partial differential equation*

$$(\Delta_n^2 + \Delta_m^2)\phi_{n,m} = 0 \quad . \quad . \quad . \quad . \quad (19)$$

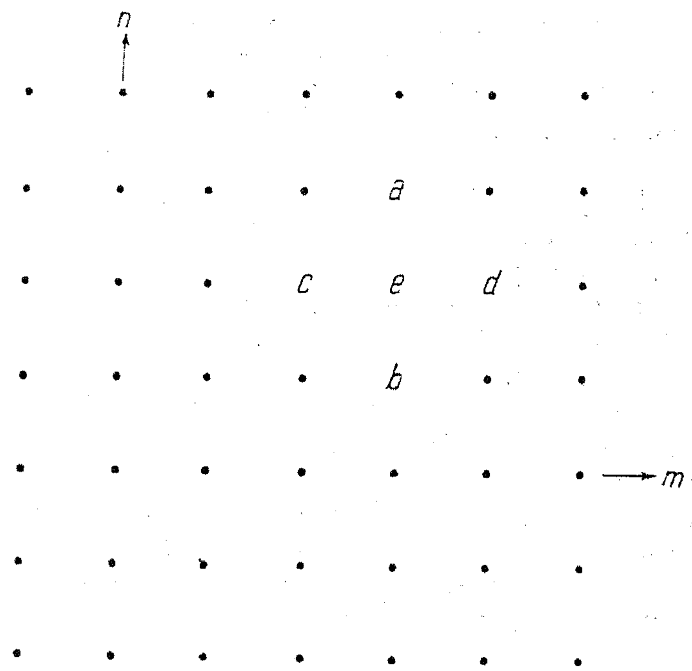


**Fig. 20.**—Any solution of the discrete two-dimensional potential equation has the property that $e$ is the arithmetical mean of $a$, $b$, $c$, and $d$.

which equation corresponds to the well-known two-dimensional *partial differential equation*

$$(D_x^2 + D_y^2)\phi(x, y) = 0 \quad . \quad . \quad . \quad (20)$$

determining all two-dimensional potential functions. We shall therefore speak again of "potential functions" $\phi_{n,m}$, meaning the solutions of (19). Our standard definitions (8) and (9) for $\Delta$ and $\Delta^2$ tell us at once that the "potential equation" (19) requires only that

$$\phi_{n+1,m} + \phi_{n-1,m} + \phi_{n,m+1} + \phi_{n,m-1} - 4\phi_{n,m} = 0 \quad (21)$$

Considering therefore again a two-dimensional rectangular lattice or net with co-ordinates $n$ and $m$ (see Fig. 20), and with values of $\phi_{n,m}$ inscribed at the corresponding co-ordinates, (21) requires that everywhere in the field the values of $\phi_{n,m}$ must be such that $a + b + c + d = 4e$

or
$$e = \tfrac{1}{4}(a + b + c + d)$$

In other words, the value of $\phi_{n,m}$ at any point must equal the mean value of the four adjacent points situated directly above, below, to the right, and to the left.* This fundamental condition (21) therefore requires considerable smoothness of the "potential function" $\phi_{n,m}$, just as in the case of the genuine potential equation (20).

Contrary to what we observed with respect to the "wave equation" (17), which expressed a relation between *four* adjacent points, the "potential equation" (19) [or the fully equivalent equation (21)] expresses a relation between *five* adjacent points.

In Fig. 21($a$) is given as an example a "potential function" in a small portion of the field ($m$, $n$). It is easy to verify that every value not lying on the circumference is the mean of the four surrounding values, e.g. $2 = \frac{1}{4}(0 + 0 + 3 + 5)$, etc. Another example is illustrated in Fig. 22 (Plate 2) showing a model made with metal pins in a wooden board, where the lengths of the pins are made equal to the different values of $\phi_{n,m}$. The tops of the pins are joined by a white cotton thread, and this model clearly indicates the property of smoothness mentioned before and which is so characteristic of all potential functions. In fact, if the cotton threads had been made of rubber and if they had been fixed with equal tension at the boundary points, and if the vertical pins were free to slide vertically through the wooden board, these pins would have taken up automatically the positions indicated in the figure and satisfying our "potential equation" (20), just as a stretched continuous rubber sheet fixed at the boundary takes up a position corresponding to the solution of the "smooth" potential equation (20).†

The discrete "potential functions" $\phi_{n,m}$ solving (19)—consider, for example, the function $\phi_{n,m}$ given in Fig. 21($a$)—possess the well-known property (Dirichlet's problem) of the "smooth" potential $\phi(x, y)$ satisfying

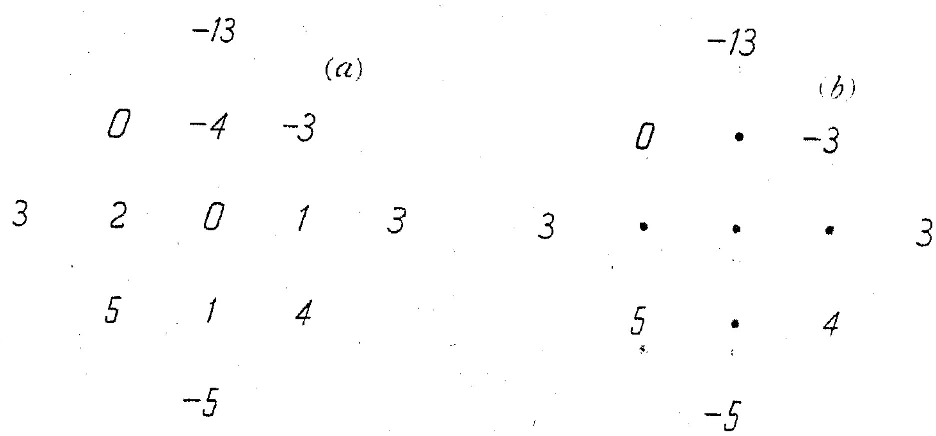


**Fig. 21**

($a$) Simple example of a solution of the discrete potential equation.
($b$) If the boundary values as represented in this figure are given, the interior points are determined in a unique way as in ($a$) (discrete "Dirichlet" problem).

* For instance, a monthly calendar like

| | | | | |
|---|---|---|---|---|
| | 4 | 11 | 18 | 25 |
| | 5 | 12 | 19 | 26 |
| | 6 | 13 | 20 | 27 |
| | 7 | 14 | 21 | 28 |
| 1 | 8 | 15 | 22 | 29 |
| 2 | 9 | 16 | 23 | 30 |
| 3 | 10 | 17 | 24 | 31 |

fulfils this condition.

† It is here assumed that the variation in the heights of the pins is so small that the tensions are not influenced by it, just as in the elementary theory of the vibrations of a string it is assumed that its deviation does not materially alter its tension.

(20), that if their value on a closed boundary is given, these values uniquely determine the values of the function inside this boundary. There is therefore only one way of completing Fig. 21(*b*), and this solution is given by Fig. 21(*a*). However, the boundary must be closed, and omitting, for example, in Fig. 21(*b*) the top value (− 13) would leave the problem undetermined. Moreover, the boundary need not, as in Fig. 22 (see Plate 2, facing page 389), have a diamond shape—any shape will suffice so long as the boundary is closed. Many interesting problems can be constructed in this way.

In addition it is an easy matter to construct arbitrary "potential functions" satisfying (19) or (21). For example, we may start by freely choosing its values on two rows (see Fig. 23); a simple trial shows that all the dotted points can then be found. For example, the point above the 9 of Fig. 23 must be such that $\frac{1}{4}(x + 0 + 3 - 3) = 9$, or $x = 36$, etc. This extension of Fig. 23 is given in Fig. 24. For a reason which will appear later on, it is advisable not to introduce too big jumps in the two rows (such as in Fig. 23), otherwise at the boundary very great values are apt to occur. Starting, however, with two rows containing integers only, ensures that everywhere in the diamond-shaped domain (which, as we saw, is fully determined by these two rows) integers only will occur.

A further detailed consideration of the example solution of (19), as given in Fig. 24, clearly illustrates many elementary properties of smooth potential functions.

In this connection it may be remarked that, whereas any analytic function of the complex variable $x + jy$ satisfies the "smooth" potential equation (20), this is not the case with the "discrete" equation (19), as a simple substitution shows at once. Although many properties of the smooth two-dimensional potentials can readily be derived from those of analytic functions, many of their properties remain which are wholly independent of these analytical problems, as exemplified by potential functions in more than two dimensions. It is exactly those properties of the smooth potentials [i.e. those independent of the fact that any analytic function of the complex variable $x + jy$ satisfies (20)] that are retained when we consider (19) instead of (20).

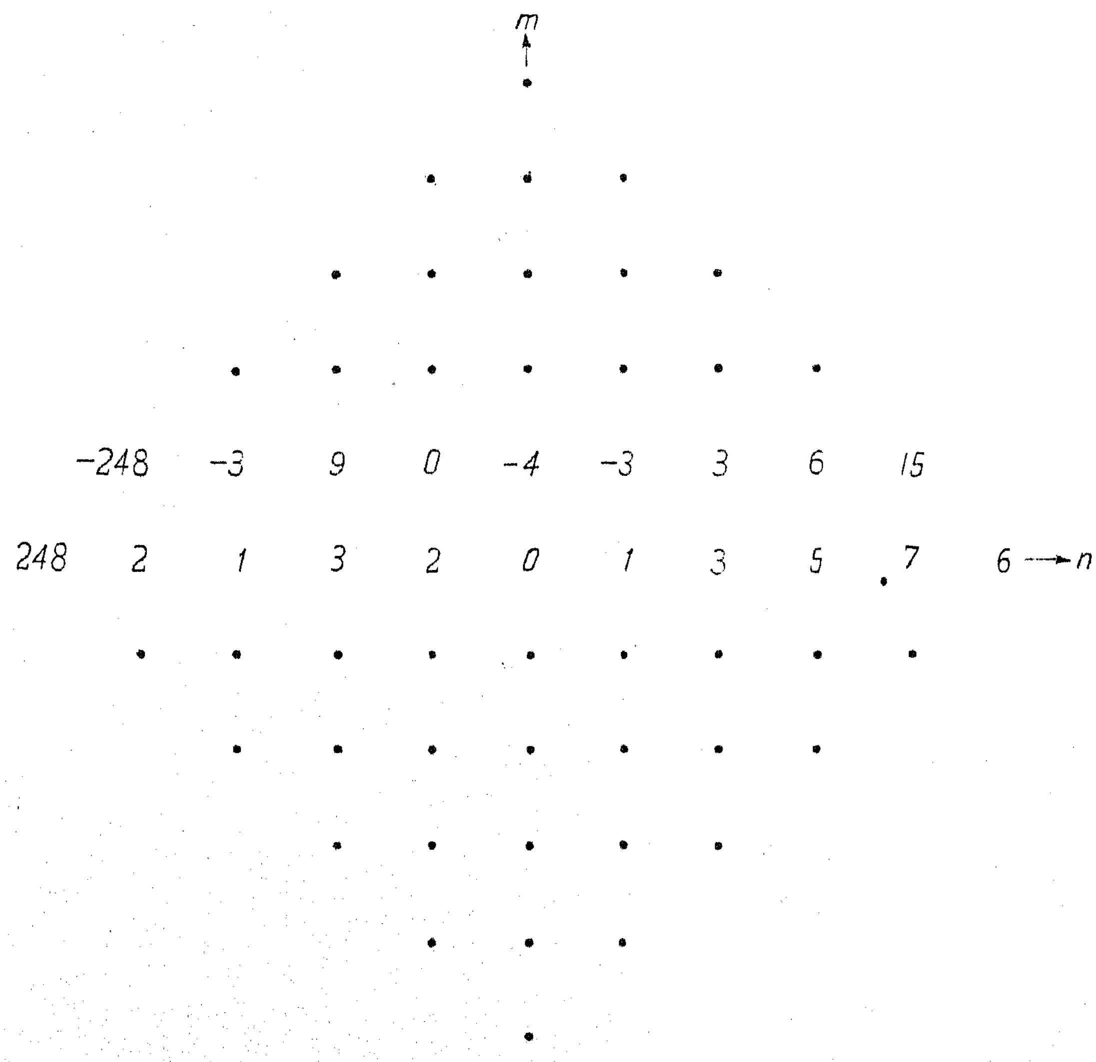


**Fig. 23.**—The values of the discrete potential on two neighbouring rows determine uniquely all the values inside the diamond-shaped figure.

Returning to Fig. 24, it will be seen that three points are marked with the letter S. These points represent "saddle points," for they clearly show a maximum in the $n$ direction and a minimum in the $m$ direction, or vice versa. Just as a two-dimensional smooth potential can show no absolute maximum or minimum, so it is here.

Further, the analogue of the property of the genuine potential that

$$\int_{ACB} \frac{\partial \phi}{\partial n} ds = \int_{ADB} \frac{\partial \phi}{\partial n} ds$$

this integral being independent of the path of integration, and where $\partial\phi/\partial n$ means the gradient normal to the path, is present also in our "potential functions."

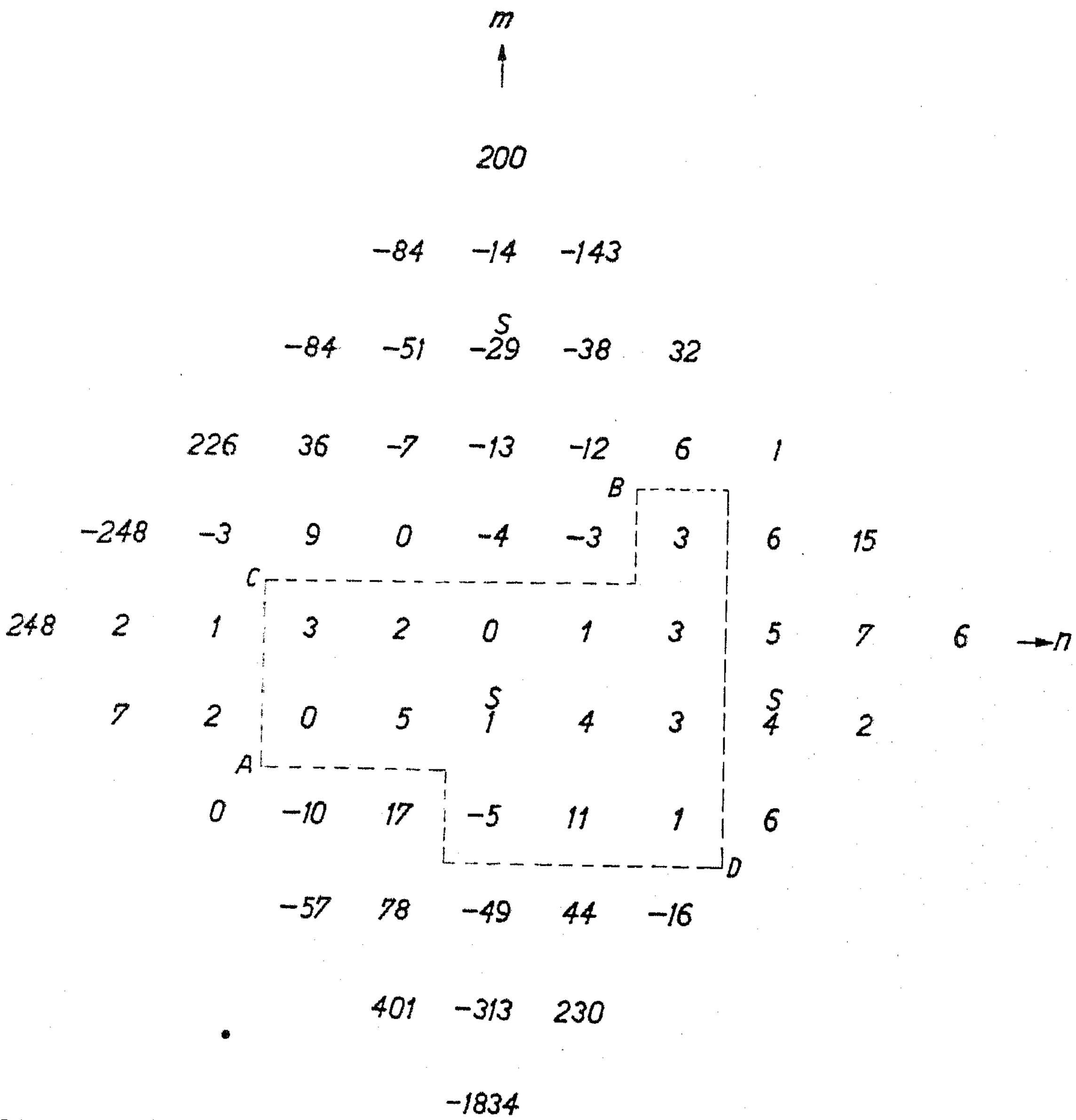


**Fig. 24.**—Example of a diamond-shaped discrete potential field larger than that shown in Fig. 21.

For, referring again to Fig. 24, the above integral over the path ACB here represents $(2-0)+(1-3)+(9-3)-(0-2)+(-4-0)+(-3-1)+(-3-3)$, and this sum equals the equivalent of the integral over the path ADB, this being represented by

$$(0+10)+(5-17)+(-5-17)+(-5+49) \\ +(11-44)+(1+16)+(1-6)+(3-4) \\ +(3-5)+(3-6)+(3-6).$$

Again the equivalent of $\oint \frac{\partial \phi}{\partial n} = 0$ (Gauss's theorem for no charge), the integral representing any closed path, follows immediately from the aforementioned property.

Fig. 24 represents a "potential field," and from such a field we can at once derive a "vector field" by taking the gradient. Now in our discrete problem there exist only the gradients $E^{(n)}$ and $E^{(m)}$ in the two directions $n$ and $m$, which, according to our basic definition (8), become

$$E^{(n)}_{n,\,m} = \phi_{n+\frac{1}{2},\,m} - \phi_{n-\frac{1}{2},\,m}$$
$$E^{(m)}_{n,\,m} = \phi_{n,\,m+\frac{1}{2}} - \phi_{n,\,m-\frac{1}{2}}$$

but we only know the values of $\phi_{n,\,m}$, where $n$ and $m$ are integers. We therefore have to consider

$$E^{(n)}_{n+\frac{1}{2},\,m} = \phi_{n+1,\,m} - \phi_{n,\,m}$$
$$E^{(m)}_{n,\,m+\frac{1}{2}} = \phi_{n,\,m+1} - \phi_{n,\,m}$$

so that we can construct the gradients, representing the corresponding electric fields at the points intermediate between two points where the "potential" $\phi_{n,\,m}$ is known. Moreover, this gradient is simply obtained by taking the difference of the values of the "potentials."

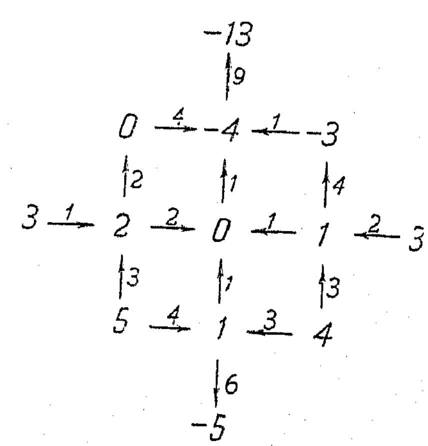


**Fig. 25.**—The discrete potential field of Fig. 21, together with the derived vector field.

We can thus, starting from the simple Fig. 21, construct the corresponding gradient or vector field as shown in Fig. 25, where the arrows representing this gradient are drawn from a higher potential towards a lower potential, and the values of the gradients are marked at the side of the arrows. Omitting further the "potential" values, while retaining the vector field, only leads to the vector

field represented in Fig. 26. If the same procedure is applied to Fig. 24, we obtain the more extensive vector field of Fig. 27, from which several classical properties of vector fields derived from a potential function may be read off.

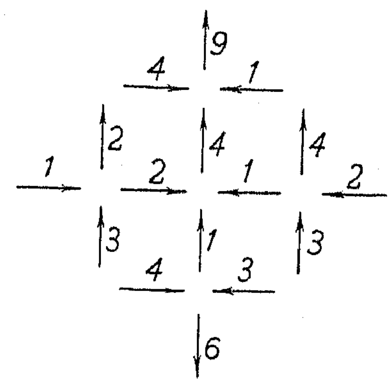


**Fig. 26.**—The vector field only, of Fig. 25.

(*a*) The total flux through a closed surface (here, with two dimensions, this closed surface becomes a closed curve) is zero. For example, consider the closed curve ACBDA: the total value of all the arrows pointing inward through this curve equals the total value of all arrows pointing outward. This, of course, corresponds

(*c*) Curl $E = 0$. This property here means that the line integral round any elementary mesh equals zero. Take, for example, the mesh G which is surrounded by the four vectors 2, 3, 1, and 0. Going round this mesh as the thin dotted curve indicates, we have to take the vectors with their proper sign (+ when going with the direction of the arrow, — when in the opposite direction). Thus we see that for the mesh G we have $2 - 3 + 1 + 0 = 0$, and this is true anywhere in the vector field of Fig. 27.

(*d*) The former property at once implies that the line integral between two points is independent of the path, e.g. $\int_{HKL} Eds = \int_{HML} Eds$. From H to L via K we have the line integral $3 + 2 + 7 + 44 - 22 + 9$ ($= 43$) and this equals the line integral from H to L via M, for here we find $4 + 1 + 4 - 1 + 9 + 26$, which again equals 43.

(*e*) $\oint Eds = 0$, or the line integral over any closed path is zero. Starting therefore from any given point and adding algebraically all the vectors we encounter on any closed path leading back again to the original point yields zero.

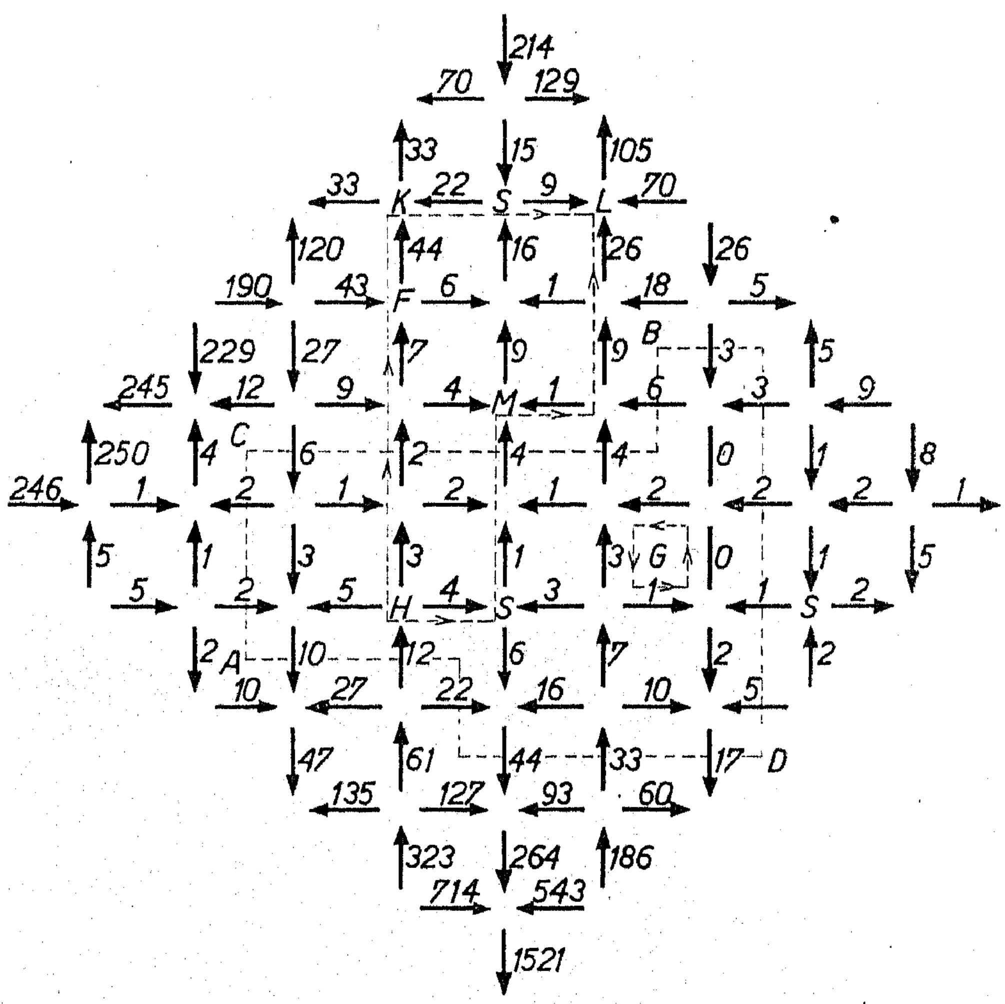


**Fig. 27.**—The vector field derived from the potential field shown in Fig. 24.

to the similar property already discussed in connection with the potential field of Fig. 24.

(*b*) Div. $E = 0$. Consider any point, such as F, where we have two arrows pointing inward, viz. 43 and 7, and two pointing outward, viz. 44 and 6, so that the total flux at this point is zero. This corresponds to the property div. $E = 0$.

Thus, several properties of vector fields derived from a potential function are easily demonstrated with the aid of Fig. 27.

All the properties discussed are at once clear to the electrical engineer if it be remembered that Fig. 27 can be considered as representing electric currents in a square-meshed homogeneous copper gauze, while Fig. 24

represents the corresponding potentials at the crossing points. Thus (*a*) represents the fact that the total current entering any closed boundary equals the current leaving this boundary, (*b*) represents the first Kirchhoff law, (*c*) represents the property that the line integral of the voltage round any elementary mesh equals zero, (*d*) represents the fact that our current problem depends upon a potential function, and finally (*e*) represents the second Kirchhoff law. The electrical interpretation thus given to Figs. 24 and 27 also illustrates the warning already given, that while constructing similar potential fields starting with two rows, great jumps between adjacent points should be avoided. For it will be clear that only by applying very great potential differences at the boundary of a copper gauze can great potential differences between two adjacent interior points be obtained.

Returning to the general problem of the "potential functions" satisfying (19), it is of interest to investigate what becomes of the very general property of all "smooth" potentials in any number of dimensions, viz. that the mean value of the potential over any more dimensional sphere equals the potential at its centre. For two dimensions, with which we are concerned here, this means that if we describe anywhere in a potential field (i.e. a domain free of charges) any arbitrary circle and take the average value of the potential over the circumference of this circle, this average value equals the value of the potential at the centre of that circle. What is the analogue of this property for our discrete "potentials" satisfying (19)? Referring to Fig. 28, it can easily be shown that here we have the property:

(*A*) *The average value over any diamond-shaped boundary equals the average value over its diagonals.*—This is to be understood that, as indicated in Fig. 28, the corners of the diamond are to be considered as belonging to the boundary only, but these corners have to be counted as half, while the centre which lies on both diagonals is to be counted twice. If, therefore, we add the values indicated in Fig. 28 with the weights as given there, the result is zero, because with this definition there are an equal number of points on the circumference and on the diagonals.

Further, a similar general property of our discrete potentials is illustrated in Fig. 29. It can be worded thus:

(*B*) *The average value over the circumference of any square equals the average value over its diagonals.*—Here the corners are understood to belong to both sides and to the diagonal. If the side of the square contains an even number of unit steps, as is the case in Fig. 29, the diagonals cut at a point belonging to the system, and this point has then to be counted twice as belonging to both diagonals. As the corners belong to both sides and to the diagonals they are given the weight (as indicated in Fig. 29) of $2 - 2 = 0$, so that the values at the corners in reality cancel out.

Theorems (*A*) and (*B*) can easily be derived with the aid of the elementary property (21) or with the aid of the property that the sums of the potentials at both sides of any closed curve are equal, as shown, for example, with regard to the closed curve ACBDA of Fig. 24.

Extending further the two-dimensional "discrete potential equation" (19) to three dimensions, this becomes

$$(\Delta_n^2 + \Delta_m^2 + \Delta_s^2)\phi_{n,m,s} = 0 \quad . \quad . \quad (22)$$

and this equation requires that the value of $\phi$ at any point shall be the average of the six surrounding points in space: directly above, below, to the left, to the right, in front, and behind. One may easily build up such numerical fields in a similar way as in the two-dimensional case, using either small cardboard cubic boxes with numbers painted on the sides (as exhibited during the lecture) or several sheets of paper, each one corresponding to a specific layer.

The theory of the partial difference equations (19)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| • | • | • | • | $\frac{1}{2}$ | • | • | • | • |
| • | • | • | 1 | −1 | 1 | • | • | • |
| • | • | 1 | • | −1 | • | 1 | • | • |
| • | 1 | • | • | −1 | • | • | 1 | • |
| $\frac{1}{2}$ | −1 | −1 | −1 | −2 | −1 | −1 | −1 | $\frac{1}{2}$ |
| • | 1 | • | • | −1 | • | • | 1 | • |
| • | • | 1 | • | −1 | • | 1 | • | • |
| • | • | • | 1 | −1 | 1 | • | • | • |
| • | • | • | • | $\frac{1}{2}$ | • | • | • | • |

**Fig. 28.**—Any discrete potential field has the property that the mean value on the circumference of the diamond-shaped figure equals the mean value on the diagonals.

and (22) developed here can further be extended to cases where there are "charges" present in the field, leading to points in the field where (19) or (22) contain a right-hand member different from zero, a question which I shall not discuss here.

I shall conclude by giving a solution of (19) of a very general nature, and one which is easily obtained in the following way.

If we try to obtain a solution of (19) of the form

$$\phi_{n,m} = e^{2n\alpha + 2m\beta}$$

it simply follows from (21) that the following relation must exist between $\alpha$ and $\beta$:

$$e^{2\alpha} + e^{-2\alpha} + e^{2\beta} + e^{-2\beta} - 4 = 0,$$

or

$$\sinh^2 \alpha + \sinh^2 \beta = 0.$$

$$\begin{array}{ccccccccc}
2-2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 2-2 \\
1 & -2 & \cdot & \cdot & \cdot & \cdot & \cdot & -2 & 1 \\
1 & \cdot & -2 & \cdot & \cdot & \cdot & -2 & \cdot & 1 \\
1 & \cdot & \cdot & -2 & \cdot & -2 & \cdot & \cdot & 1 \\
1 & \cdot & \cdot & \cdot & -4 & \cdot & \cdot & \cdot & 1 \\
1 & \cdot & \cdot & -2 & \cdot & -2 & \cdot & \cdot & 1 \\
1 & \cdot & -2 & \cdot & \cdot & \cdot & -2 & \cdot & 1 \\
1 & -2 & \cdot & \cdot & \cdot & \cdot & \cdot & -2 & 1 \\
2-2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 2-2
\end{array}$$

**Fig. 29.**—Any discrete potential has the property that the mean value on the boundary of any square equals the mean value on its diagonals.

Hence (19) is satisfied by

$$\phi_{n,m} = e^{2(n \operatorname{arc\,sinh} \lambda + m \operatorname{arc\,sinh} j\lambda)}$$

where $\lambda$ has any arbitrary complex value. From this another solution can be derived in the form

$$\phi_{n,m} = \left(\frac{s+j}{s+j^3}\right)^{n+m} \left(\frac{s+j^4}{s+j^2}\right)^{n-m}$$

where again $s$ may have any arbitrary value.

Hence, solutions of (19) of a very general nature are

$$\phi_{n,m} = \int_{\lambda_1}^{\lambda_2} e^{2(n \operatorname{arc\,sinh} \lambda + m \operatorname{arc\,sinh} j\lambda)} \psi_1(\lambda) d\lambda \quad . \quad (23)$$

and

$$\phi_{n,m} = \int_{s_1}^{s_2} \left(\frac{s+j}{s+j^3}\right)^{n+m} \left(\frac{s+j^4}{s+j^2}\right)^{n-m} \psi_2(s) ds \qquad (24)$$

where $\psi_1(\lambda)$ and $\psi_2(s)$ are arbitrary functions and $\lambda_1$, $\lambda_2$, $s_1$, and $s_2$, are arbitrary complex constants but independent of $n$ and $m$.

It appears that a further investigation of (23) and (24) might lead to the discovery of interesting properties of circuits such as those considered above. This would seem to illustrate the view of your famous philosopher and mathematician Bertrand Russell, who, if my memory serves me right, expressed himself more or less as follows:

" A mathematician is never so happy as when he does not know what he is talking about."

## APPENDIX

In Section (7) attention was drawn to the fact that if either the real part or the imaginary of an impedance is known, the other part can be found. In fact the following relations exist:—

If $Z(p)$ is an impedance, and

$$\begin{aligned} Z(j\omega) &= R(\omega) + jX(\omega) \\ &= |Z(j\omega)| e^{j\phi(\omega)} \end{aligned}$$

where $R(\omega)$ represents the real part and $jX(\omega)$ the imaginary part, and $|Z(j\omega)|$ represents the modulus of the impedance and $\phi(\omega)$ its phase, then we have

$$\begin{aligned} Z(p) &= \frac{2p}{\pi} \int_0^{\infty} \frac{R(\omega)}{p^2 + \omega^2} d\omega \\ &= \frac{2}{\pi} \int_0^{\pi/2} R(p \tan \psi) d\psi \\ &= C - \frac{2}{\pi} \int_0^{\infty} \frac{X(\omega)}{p^2 + \omega^2} \omega d\omega \end{aligned}$$

where $C$ is a constant which has to be given as well if the imaginary part $X(\omega)$ only is known. These formulae therefore express the complete impedance $Z(p)$ as a function of the real part or of the imaginary part.

Again we have

$$X(\omega) = \frac{2\omega}{\pi} \int_0^{\infty} \frac{R(\lambda) - R(\omega)}{\lambda^2 - \omega^2} d\lambda$$

$$R(\omega) = C - \frac{2}{\pi} \int_0^{\infty} \frac{\lambda X(\lambda) - \omega X(\omega)}{\lambda^2 - \omega^2} d\lambda$$

which formulae give the imaginary part and the real part if either the real part or the imaginary part, respectively, is known.

In addition, the relations exist:

$$\log Z(p) = \frac{2p}{\pi}\int_0^\infty \frac{\log |Z(j\omega)|}{p^2+\omega^2}d\omega$$

$$= C - \frac{2}{\pi}\int_0^\infty \frac{\omega\phi(\omega)}{p^2+\omega^2}d\omega$$

expressing the logarithm of the total impedance if either its modulus or its phase is known. In the latter case again a knowledge of the constant $C$ is required.

Finally we have

$$\phi(\omega) = \frac{2\omega}{\pi}\int_0^\infty \frac{\log |Z(j\omega)| - \log |Z(j\lambda)|}{\lambda^2-\omega^2}d\lambda$$

$$\log |Z(j\omega)| = C - \frac{2}{\pi}\int_0^\infty \frac{\lambda\phi(\lambda) - \omega\phi(\omega)}{\lambda^2-\omega^2}d\lambda$$

giving the phase of the impedance when its modulus is known, and its modulus when its phase is given. In the latter case again a knowledge of $C$ is required in order to specify the problem completely.

Similar relations exist with respect to the admittance.

# CONSTANT TEMPERATURE: A STUDY OF PRINCIPLES IN ELECTRIC THERMOSTAT DESIGN; AND A MAINS-OPERATED ISOTHERMAL CHAMBER CONSTANT TO ONE-THOUSANDTH OF A DEGREE CENTIGRADE

By L. B. TURNER, M.A., Member.

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## SUMMARY

The paper is concerned with the design of apparatus for maintaining a chamber at a nearly constant temperature, above the ambient temperature, despite fluctuations of its environment. After brief discussion of thermostats in general, attention is confined to electrically-operated devices in which the temperature-sensitive element enters into a bridge configuration: departure of the temperature from the assigned working value, by throwing the bridge out of balance, effects a corrective change in the heat supply. By analysis and experiment published elsewhere, the author has shown that in such systems hunting, necessarily present if the heat supply is controlled in discrete quantities, will occur also if there is a continuous relation between temperature and heat supply, provided that the control sensitivity exceeds a critical threshold value. The bearing of this result on the design of fine temperature-regulating apparatus is examined, and the frequency and amplitude of hunting are considered. The relations of the factors determining the residual inconstancy of temperature are analysed. Amongst the conclusions reached are (roughly stated): (*a*) hunting does not depend on the heat capacity of the chamber; (*b*) the residual inconstancy does not depend on thoroughness of thermal insulation of the chamber; (*c*) there is a single figure of merit measuring the intrinsic effectiveness in resisting changes of ambient temperature and of supply voltage; (*d*) of these two factors, the former is of less practical importance than the latter; (*e*) the effect of temperature-difference between the chamber and the temperature-sensitive element must not be ignored; (*f*) identification of the temperature-sensitive resistor with the resistor carrying the controlled current, advocated by some previous workers, is wrong in principle.

The author's apparatus is described: it is the outcome of an attempt to obtain the smallest possible inconstancy consistent with derivation of electric supplies from the a.c. mains alone, and is in accord with the principles reached in the foregoing study. Difficulties experienced in measuring small temperature-changes are reported, and the significance of readings of mercury thermometers is assessed. Finally, it is shown that the author's design could be modified for large size and high temperature.

A term not in common use has, for the sake of brevity, been employed throughout the paper: a "millideg." (to be pronounced as written) stands for a thousandth of a degree Centigrade.


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CONTENTS—*continued*



## (1) INTRODUCTION

Automatic temperature control is widely used in all sorts of domestic, industrial, and scientific processes. The general principle is, obviously, to associate with the body or chamber whose temperature is to be fixed some temperature-sensitive device serving to increase or decrease a supply of heat to the body whenever its temperature passes a selected value. The temperature-sensitive heat-controlling element may take one of many forms. These range from an elastic capsule of volatile liquid operating a gas valve or a switch (as in a chicken incubator or a hot-water system) to a Wheatstone bridge with galvanometer, light beam, and photocell (as in a high-temperature furnace at the National Physical Laboratory, and in a thermostat for a quartz oscillator in the Post Office Engineering Department).

In recent years valve-operated tuning forks and quartz crystals have been intensively developed as master oscillators for wireless transmitters highly constant in frequency, and for time- and frequency-measuring instruments so precise as to rival even the astronomical clock. These developments have required the use of a chamber in which the master oscillator can be housed, protected from atmospheric changes, especially of temperature. For of all the variables which are contended with in the struggle for ever more constant frequency, it seems that so far ambient temperature has been the final obstacle. It may be that the use of recently-discovered crystal-cuts giving nearly zero temperature-coefficient will invalidate this statement; but it is thought to be true of at least most oscillators at the present time.*

* In a report of the British Air Ministry on the performance of the Lucas-Sullivan multivibrator, quoted in Messrs. H. W. Sullivan's catalogue of 1935–36, it is stated: "None of the observations differed by more than 3 parts in $10^7$. This at the time represented the best accuracy that could be expected, as the probable error was controlled by the accuracy with which the temperature of the crystal was known."

On this account alone the design of temperature-controlled chambers of great constancy is a subject of present interest in applied physics and in engineering practice; and it can hardly be doubted that the provision of highly constant temperature will be welcomed in other fields, provided that the complexity and manipulative difficulties of the apparatus can be sufficiently reduced. Biologists are already interested in the maintenance of extremely constant temperature; for minute changes of heat production in living tissue, detected by thermocouple, have been used as an index of vital process; and these changes can be measured only when the body under examination is protected from temperature fluctuation imposed from outside.* A like need for constant temperature has been experienced in investigations on the storing of apples and peas, in which also small temperature-changes have been observed with the aid of thermocouples.† The author is informed that measurement of heat production is likely to be a valuable method in researches on plant physiology—a method which has so far been very little explored on account of the difficulty of obtaining the necessary constancy of temperature, which must be maintained for long periods.

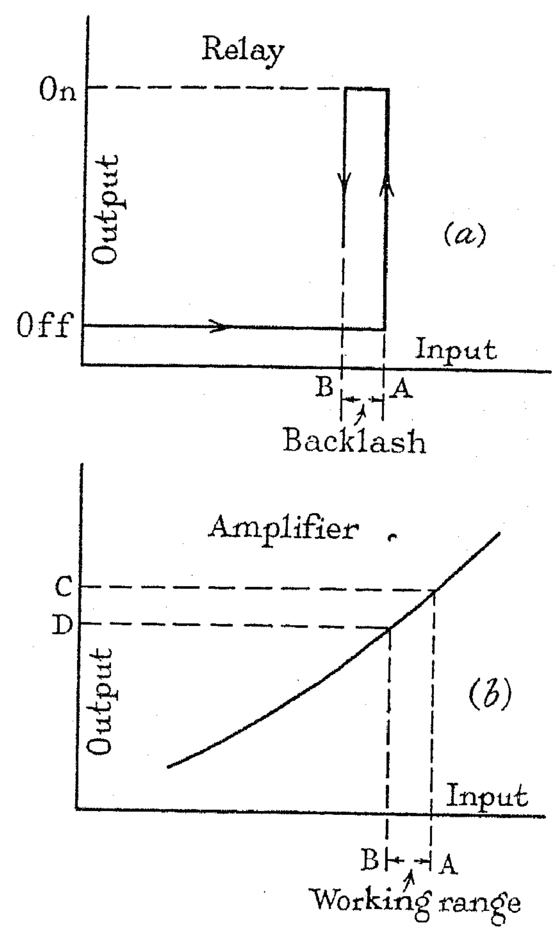



**Fig. 1.**—Limitations of relay and amplifier.

There is a fundamental and insurmountable obstacle to the attainment of perfect constancy of temperature, whatever form the thermostat may take. It must comprise something in the nature of a relay, i.e. a translating apparatus in which there is a discontinuity in the relation between input and output; or something in the nature of an amplifier, i.e. a translating apparatus in which the output varies continuously with the input. Now every form of relay exhibits some backlash [Fig. 1(*a*)], i.e. an inequality between the thresholds of make and break, of on and off; and every form of amplifier has finite sensitivity [Fig. 1(*b*)]. In each arrangement, therefore, the requisite change of output to compensate for, say, a change of ambient temperature, cannot be effected until the would-be constant temperature has changed by a finite amount. Only by making the length AB zero in Fig. 1(*a*), or the ratio AB/CD zero in Fig. 1(*b*), could the thermostat be made completely effective in resisting changes of temperature.

Before the development of thermionic-valve technique it was easier to contrive sensitive thermostats of the relay type than of the amplifier type; and probably the latter are still comparatively rare. A particularly simple form of the relay type is the liquid-expansion thermostat with an electrical contact. This is shown diagrammatically in Fig. 2. A voluminous "bulb" A is filled with a liquid such as toluene (which is superior to mercury in having smaller density and larger coefficient of thermal expansion), and is closed by a column of mercury B standing above it in a fine-bore tube. Electrical contact with the surface of the mercury as it rises with increase of bulb temperature is made to cut off a supply of heating current in the resistor C, which is in more or less close thermal contact with the bulb A and the body D whose temperature it is desired to hold constant. We will provisionally make the simplifying assumption that A, C, and D have always sensibly the same temperature. Assuming that the height of the mercury is a single-valued function of the temperature of the toluene, if, on rise and fall of the mercury, make and break were to occur at exactly the same level, perfect constancy could be attained. Actually, however, owing to dirt on the surface of the mercury and to surface tension and other effects, make and break do not occur at the same mercury level. There is backlash; and hunting over the range of the backlash is unavoidable. The effect is reduced, but cannot be wholly removed, by giving the contact wire a vertical reciprocating motion by some independent mechanism.

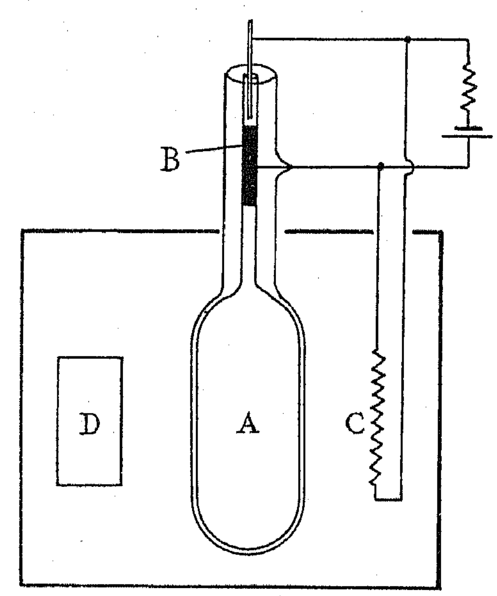



**Fig. 2.**—Principle of liquid-expansion thermostat.

A more serious imperfection in the real thermostat lies

* Apparatus devised for this purpose is described by A. V. Hill: *Proceedings of the Royal Society*, B, 1928, vol. 103, p. 121; and by T. P. Feng and A. V. Hill: *ibid.*, 1933, vol. 113, p. 358.

† See Annual Report of Food Investigation Board, 1928, p. 53; and 1932, p. 153.

in the impossibility of obtaining the ideal uniform temperature throughout the heater-bulb-body mass. As drawn in Fig. 2, the bulb A is below the standard temperature; consequently heat is being supplied at C. By the time contact is made, the C region will be hotter than A, heat will continue to flow into A, and the mercury will overshoot the contact-making level. The hunting is therefore more violent than that which would be caused by contact backlash alone. This augmentation of the hunting is made less severe, but cannot be eliminated, by improving the thermal contact between A and C. In practice this is commonly done by immersing A, C, and D in a bath of liquid maintained in vigorous circulation or turbulence.* An interesting variation of this course has been adopted in a thermostat where it is desired to limit the inconstancy (over short times) to 10 millideg., and the chamber is a room occupied by the experimenter with distribution of heat by turbulent air. The hunting period was reduced from some 3 minutes to 10 or 15 sec. by the device of locating an important fraction of the " bulb " A within the blast of hot air proceeding directly from the concentrated heater C.† Such

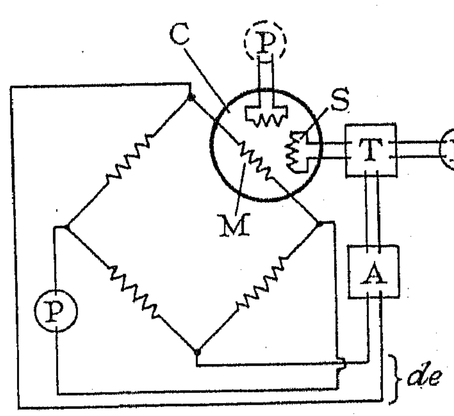



**Fig. 3.**—Components of electric-bridge thermostat.

means for reducing the hunting period must, *pari passu*, favour control of the mean temperature of the heater C at the expense of the chamber D.

The hunting phenomenon is well known, and designers have regarded it as a serious obstacle and have endeavoured to avoid it by providing amplifier action in place of relay action. This would be given in Fig. 2 if the resistance of the mercury-wire contact did not pass discontinuously from infinity to zero, but were made to change continuously with the level of the mercury, as by the provision of a partially insulating covering on the wire.‡

The author has no personal experience of the behaviour of mercury-contact forms of thermostat; but he would expect to find that their use for fine temperature regulation (e.g. to 1 millideg.) unattended over long periods of time would involve either the inconvenience of a very unwieldy bulb and distribution of heat by liquid convection,* or disastrous inconstancy of behaviour of the contact. In apparatus used in the Department of Physiology, University College, London, the mercury contact is avoided by making the moving mercury column continuously obstruct more or less an orifice which conveys a stream of coal gas to a heating jet.†

Where a turbulent liquid bath is not permissible, heat distribution must be effected by conduction. The most propitious form of thermostat then seems to be a temperature-sensitive electrical resistor, whose value somehow determines the current in a heating resistor. Henceforth in this paper only this form of thermostat is considered. It will be convenient to call the resistor through which the controlled heating current passes the "slave coil," and the temperature-sensitive resistor whose commands the slave coil obeys the "master coil." The chamber or body whose temperature is to be held constant is here called the "isothermal chamber." The master coil and the slave coil must be related together by apparatus, here called the " translator," whose input is a signal derived from the master coil and whose output is the heating current in the slave coil. The fundamental constituents of the whole thermostat are shown diagrammatically in Fig. 3. Here M is the master coil, S the slave coil, C the isothermal chamber, T the translator with (perhaps) an amplifier A, and P is a source of power.

## (2) THE ISOTHERMAL CHAMBER AND HUNTING

In Part IV of a comprehensive paper on the work carried out with crystal oscillators in the Post Office up to 1934, Messrs. Booth and Dixon give a classification and summary descriptions of the various temperature-regulated ovens which were investigated. These comprise thermostats of the relatively crude bimetallic-strip type, capable of regulation to within perhaps $\pm\frac{1}{4}$ deg. C.; and five forms of thermostat of the electric-resistor type. They set out a number of general principles, suggested by their experience, which should govern the design of such apparatus.‡ Of these five forms of thermostat, the first four all feed heat to the slave coil in discrete quantities by the mediation of an electromechanical relay as part of the translator. In the fourth [their Fig. 36(*d*)], the connection between bridge and relay is by galvanometer, beam of light, and photocell; and of this they remark: " The sensitivity of this type may be made enormously greater than that of any of the other types mentioned." As might be expected, however, they here encounter the hunting difficulty. " If the thermal lag of the oven is too great, however, it may not be possible to use the full sensitivity of the galvanometer." No figures are given for the amplitude of hunting tolerated under working conditions, but it is stated that " in Post Office ovens

* At the National Physical Laboratory there is a large and elaborate apparatus operating on this basic principle. It is used to house an oscillator (20 kilocycles per sec.) in the form of a bar of invar 1 m. long. It is believed that the temperature of the bar has been held constant to within 5 millideg. during 2 years.

† T. DEIGHTON: " A Precision Thermostat for the Temperature Regulation of a Room," *Journal of Scientific Instruments*, 1936, vol. 13, p. 298. The air throughout the room is rendered violently turbulent by nine electric fans.

‡ A description of an apparatus operating on this principle is given by F. R. WINTON: " A Thermostat Constant to One-thousandth of a Degree Centigrade," *Journal of Scientific Instruments*, 1929, vol. 6, p. 214.

* In the N.P.L. apparatus mentioned above, the bulb is in the form of some 36 ft. of tubing containing about $2\frac{1}{4}$ pints of toluene.

† A. V. HILL: " A Thermal Method of Measuring the Vapour Pressure of an Aqueous Solution," *Proceedings of the Royal Society*, A, 1930, vol. 127, p. 9. The temperature of the water bath in this apparatus is said to be held constant to 1 millideg. all day long. It seems, however, that this conclusion is based on the constancy of reading of a Beckmann thermometer with 0·002 deg. C gradations. The reliability of such evidence is questioned in Section (8) below.

‡ See " Crystal Oscillators for Radio Transmitters," *Journal I.E.E.*, 1935, vol. 77, p. 197. The construction of the present author's apparatus had been begun before the paper by Messrs. Booth and Dixon appeared. It will be seen below that the conclusions he reaches are in marked disagreement with some of the views on thermostat design expressed by these workers. But he wishes to acknowledge the help he has received from a study of their paper, which contains the only approach to a systematic examination of the problem he has encountered.

the average heat-supply cycle is 1 per 3 minutes." The fifth, Mr. Dixon's "thermautostat," departs from the fourth in two very interesting respects: the translator has continuous (amplifier-like) action, and the master coils themselves act as the slave coil.

A form of temperature control very similar to the last in respect of the identification of the slave and master coils is in use at the National Physical Laboratory for regulating a furnace working in the neighbourhood of 1 000° C. The heat is furnished by a platinum coil forming one arm of a Wheatstone bridge. Part of the power supplied to the bridge is controlled (discontinuously) by the resistance of the platinum coil, with the aid of galvanometer mirror, photocell, and gas-filled valves.

The author's designs were originally prompted by his

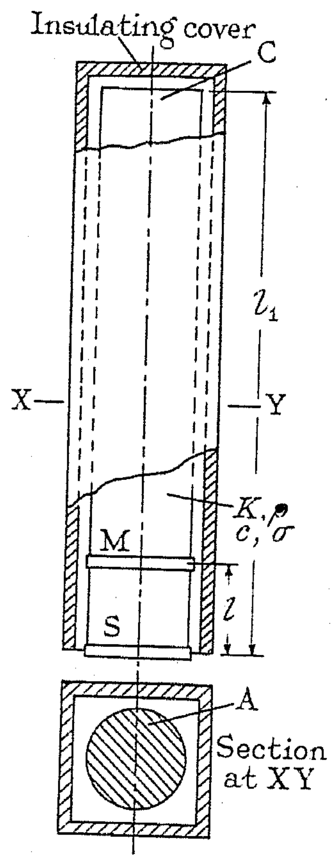



**Fig. 4.**—"Academic oven" for hunting experiments.

possession of a mains-operated instrument which could be used as an elegant translator for giving amplifier-like control of the heating current.* Conscious of the trouble due to hunting with relay control, he supposed at first that by the substitution of continuous (amplifier-like) control hunting was theoretically avoidable, however great the sensitivity of control might be made. Experiment soon showed that this was a mistake. With any relative disposition of the master coil and the slave coil, when the control sensitivity was made sufficiently large, thermal oscillation made its appearance.

This unexpected phenomenon was investigated with the help of a dummy oven representing a real oven, but shaped so as to be tolerably amenable to mathematical analysis, and with exaggerated separation between the master and slave coils in order to facilitate experimental observation of the hunting oscillation. This dummy, the "academic oven," is shown in Fig. 4. C is an aluminium-alloy cylinder of length $l_1 = 29$ cm., and cross-sectional area $A = 20$ cm$^2$, representing the isothermal chamber. S is the slave coil and M the master coil, separated by a distance $l$. It was arranged that the heating power $P_1$ in the slave coil was controlled continuously by the temperature $\theta$ of the master coil. The control sensitivity $dP_1/d\theta$ was variable, and roughly known, over a very wide range. Somewhat complicated analysis* yielded the following approximate results: If $l = l_1$ or if $l < 0\cdot55\, l_1$, thermal oscillation must arise when the control sensitivity per unit area of cross-section, $\frac{1}{A}\frac{dP_1}{d\theta}$, is increased beyond a critical value $s$, where $s = 17\cdot6K/l$ or $35K/l$ respectively; and in both cases the period of the oscillation is $T = 0\cdot57l^2\rho c/K$. Here $K$ is the thermal conductivity of the material of the cylinder, $\rho$ is its density, and $c$ its specific heat. If $l = l_1$, these formulae (slightly modified to allow for

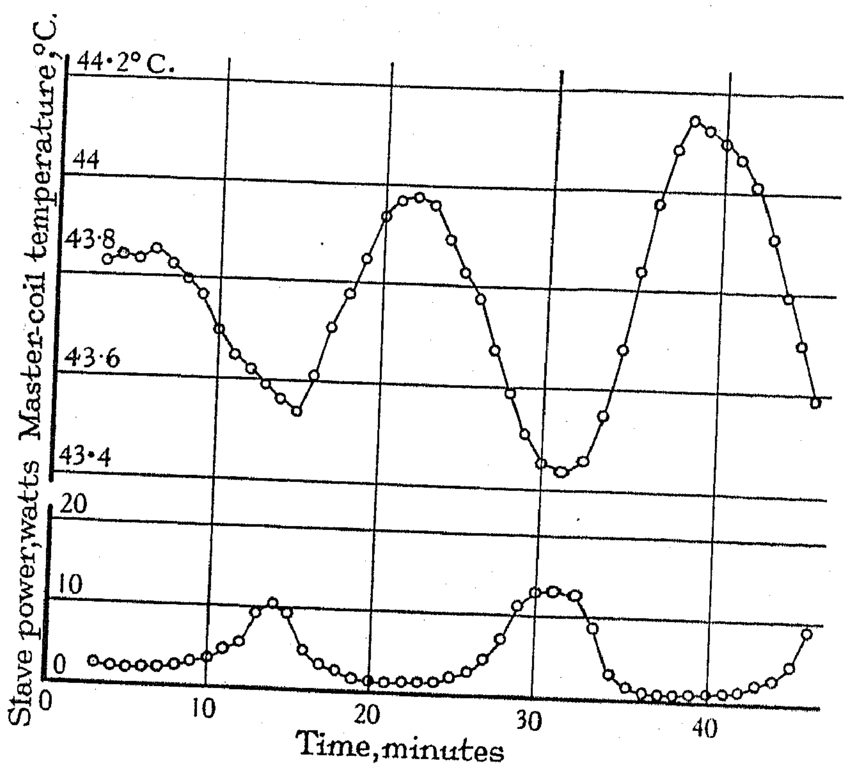



**Fig. 5.**—Hunting with amplifier-like control.

imperfect heat insulation) give $0\cdot19$ calorie per sec. per cm$^2$ per deg. C. for $s$, and 15 minutes for $T$. Fig. 5† shows the observed oscillation which supervened when the control sensitivity was gradually increased to just above the threshold value. $s$ was roughly measured as $0\cdot1$, and it is seen from the figure that $T$ was 17 minutes. When $l$ was $4\cdot7$ cm., $s$ was observed to be about $3\cdot1$, and $T$ was 31 sec.

The above formulae for $s$ and $T$ provide a great deal of guidance for the design of a real oven. No severe distortion of the conditions assumed in the analysis is involved on changing the academic oven of Fig. 4 into a real oven as in Fig. 6, where the white and black circles represent the master and slave coils respectively. When these are closely intermingled, the disposition of Fig. 6 must be fairly equivalent to that of Fig. 4 with $l$ very

* L. B. Turner: "The Control of a Gasfilled Valve through a Phase-shifting Input Valve," *Wireless Engineer*, 1937, vol. 14, p. 229.

* See L. B. Turner: "Self-oscillation in a Retroacting Thermal Conductor," *Proceedings of the Cambridge Philosophical Society*, 1936, vol. 32, p. 663. (Experimental details are included in the paper.)

† Figs. 5 and 8 are reproduced, by permission, from the paper quoted above.

small. Accepting, then, the analysis made for Fig. 4 as at least qualitatively applicable to Fig. 6, we can reason as follows. It is obvious that we wish to make the control sensitivity as large as possible; at the same time we wish either to avoid self-oscillation altogether, or, if this cannot be managed, to make the period $T$ as small as possible. Now $s = 35K/l$; so the greatest control sensitivity which could be provided without causing hunting is proportional to the conductivity of the material of the chamber, and to the reciprocal of the separation of the master and slave coils. The coils should therefore be in close juxtaposition, and be wound in good thermal contact on a chamber of high conductivity. If, despite this disposition, so great a control sensitivity is employed that oscillation does occur, its frequency is proportional to $K/(\rho c l^2)$. The exact numerical value to be assigned to $l$ is, indeed, not known; but clearly it decreases without limit as the master and slave coils are brought into closer and closer thermal relation. $K/(\rho c)$, which is the "diffusivity" $\sigma$ of the material, should be as large as possible. The conductivity and the diffusivity of some materials are tabulated in Appendix 1. It is clear that copper or aluminium is likely to be selected for the isothermal chamber.

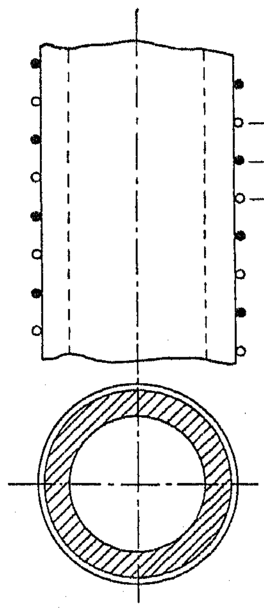



**Fig. 6.**—"Academic oven" of Fig. 4, transformed into real oven.

In the above considerations the thickness of the cylinder wall has been without practical significance.* Excessive thickness is undesirable on the obvious grounds of weight, volume, and cost, and also because the larger the heat capacity the longer is the time required to reach a steady temperature on warming up from the cold, or on changing the working temperature of the chamber. On the other hand, adequate thickness is called for (*a*) to moderate temperature gradients caused by any lack of uniformity of distribution of cooling and heating over the surface of the chamber, especially with respect to the flat ends, where it is not very practicable to spread the master and slave coils; and (*b*), if hunting is to occur, to attenuate the cyclic changes of temperature to a negligible amplitude at the interior surface of the chamber.

The quantitative significance of these considerations is best seen from a numerical example. Suppose the cylinder is of aluminium, the external diameter and length are 10 cm. and 16 cm. respectively, the walls are of uniform thickness 1 cm., and the total heat loss is $0 \cdot 7$ calorie per sec. ($= 2 \cdot 9$ watts) uniformly distributed over the whole surface.* The end areas (Fig. 7) are each 78 cm$^2$, and the cylindrical surface is 500 cm$^2$. There must be conduction of $0 \cdot 7 \times (78/656) = 0 \cdot 083$ calorie per sec. from B towards C. If $\theta$ is the temperature at a distance $x$ from the middle A, by considering the flow across an element $dx$ we find, in millideg.-cm. units, $\theta = \theta_A - 0 \cdot 182x^2$. The temperature-drop $(\theta_A - \theta)$ is plotted as the dotted curve in Fig. 7. For the flat ends, if $\theta$ is the temperature at a distance $r$ from C, by considering the flow across an element $dr$ we find $\theta = \theta_C + 0 \cdot 286r^2$. The further drop $(\theta - \theta_C)$ also is shown by the dotted curve. The greatest temperature-difference $(\theta_A - \theta_C)$ is about 15 millideg. It is, of course, possible to produce uniformity of temperature along the cylinder by a suitably non-uniform distribution of the winding. In our example, if this were done, and if the top and bottom of the chamber were doubled in thickness, an extremely close approach to uniform temperature would be obtained.

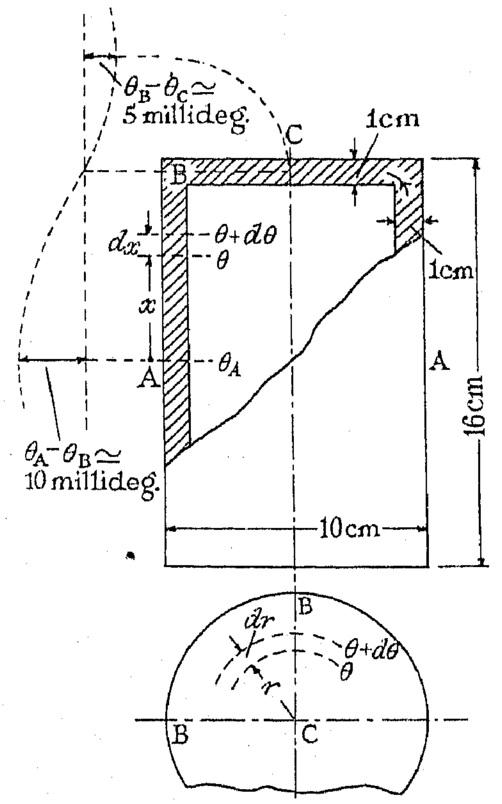



**Fig. 7.**—Heat flow in numerical example.

Turning now to consideration (*b*) above, namely, the effect of thickness of wall on penetration of the hunting oscillation to the interior surface of the chamber, it is seen that this is a case of cyclic temperature-changes propagated by conduction in one dimension. Analysis, outlined in Appendix 2, shows that if the attenuation of the heat wave in passing from the outside to the inside

* This conflicts with the second part of Messrs. Booth and Dixon's 6th precept (*Journal I.E.E.*, 1935, vol. 77, p. 230): "The thermal mass of the elements and associated thermal surface should not be too great in order that the period of operation of the thermostat should be as rapid as possible."

* These and other numerical examples represent roughly the actual conditions in the author's apparatus subsequently described.

surface of the wall of the chamber is fairly large, the ratio between the amplitudes at the two surfaces of the wall is

$$\frac{1}{2}e^{\sqrt{\left(\frac{\omega}{2\sigma}\right)}l_1}$$

where $l_1$ is the wall thickness, $\omega/(2\pi)$ is the hunting frequency, and $\sigma$ is (as before) the diffusivity $K/(\rho c)$ of the material.

At first sight this suggests that low diffusivity is favourable; but it is not so; for, as we have seen, the hunting frequency is itself proportional to the diffusivity. Changing the material of the cylinder, therefore, does not affect the attenuation in its wall. Returning to the numerical example (Fig. 7), for a hunting frequency of 1 cycle per sec. we find an attenuation (ratio of amplitudes) of $\frac{1}{2}e^{1\cdot95}(= 3\cdot5)$. We shall see that in the author's apparatus the hunting frequency is rather more than 1 cycle per sec.; and, as the amplitude at the outer surface is of the order $\frac{1}{2}$ millideg., it is reduced to something like $\frac{1}{7}$ millideg. at the inside, and little advantage as regards hunting would accrue from an increase of wall thickness. On the other hand, in a chamber where the hunting frequency is very low (for example, the 1/180 cycle per sec. of the Post Office ovens already referred to), 1 cm. of aluminium has no appreciable effect.

A thick wall is desirable, without respect to hunting, for reducing temperature gradients along the walls—consideration (*a*) above—but with low hunting frequency other steps must be taken to protect the contents from the temperature oscillation of the chamber. In the Post Office apparatus shown in Fig. 35 of Messrs. Booth and Dixon's paper,* operating with a bimetallic-strip contact thermostat, there is no such protection, and one would imagine there must be serious temperature oscillation of the brass slab on which the crystal is mounted. The quoted inconstancy is here $\pm$ 0·25 deg. C. The usual course is to interpose a lining of celotex or other insulating material between the intermittent heaters and the would-be isothermal contents of the chamber. In the Post Office oven shown at Fig. 37(*b*) in the same paper there is such an insulation, of wood and air.

The attenuation of the insulating layer may be augmented by giving it an inner metal lining possessing considerable heat capacity; but even without any such addition an insulating layer may be very effective. Thus if, in Fig. 7, the metal walls were lined with 1 cm. of celotex, and the chamber were empty of all else, this insulating lining would divide the temperature amplitude at the inner surface, caused by hunting of even such low frequency as 1/180 cycle per sec., by about 40. If the frequency were 3 times as great (1 cycle per min.), the amplitude would be divided by about 1 000. Objections to such a lining are: (i) it would occupy over half the space within the chamber; (ii) it would vastly prolong the process of bringing the contents of the chamber to the steady temperature after starting-up or changing the working temperature; and (iii) if the apparatus whose temperature is to be fixed itself contains a source of heat (as, for example, if it is a quartz oscillator), this apparatus clearly ought to be given the closest possible thermal contact with the master coil. In the author's opinion, an internal insulating lining should be regarded as an evil feature, imposed only by the existence of lamentable hunting conditions.

* *Loc. cit.* on page 401.

## (3) GENERAL THEORY OF CONTINUOUS THERMOSTAT ACTION

We have seen that thermostats operating in the continuous regime (amplifier-like action) do hunt if the control sensitivity is made sufficiently great; but that by moderating the sensitivity they can be worked without hunting. The sole cause of hunting, when it occurs in the continuous regime, is the existence of thermal separation between the slave and master coils. As $l/K$ (Fig. 4) approaches zero, the control sensitivity at the oscillation threshold approaches infinity, i.e. the conditions for hunting do not obtrude; and as $l^2/\sigma$ approaches zero, the frequency of the oscillation approaches infinity, i.e. the hunting (if any) tends to become innocuous. It is assumed in the last statement that increase of frequency does not involve an offsetting increase in amplitude. Now the analysis referred to in Section (2) leaves the question of amplitude of oscillation untouched; it refers only to the incidence of oscillation. Experiments with the "academic oven," however, confirm the natural suspicion that large oscillation frequency and small oscillation amplitude go together. When $l$ in Fig. 4 was reduced from 29 cm. to 4·7 cm., thereby increasing the oscillation frequency some 30-fold, it was possible to adjust the control sensitivity so that a steady oscillation of quite small amplitude was obtained, e.g. of the order of 3 millideg. at the master coil. It seems, therefore, that the correct course in planning a thermostat of the amplifier type is not necessarily to limit the control sensitivity in order to avoid hunting. It may be that the highest control sensitivity which can be produced is the right sensitivity to adopt; it depends upon how close a thermal contact is attainable between the master coil and the slave coil.

The author's design of chamber (see Fig. 12) was conditioned by the desire to obtain the closest practical thermal union between the chamber, the master coil, and the slave coil. The contact is very close indeed: so close that, although the control sensitivity has been made as large as is practicable, when working in the amplifier regime hunting does not occur; and there is experimental reason to think that, if the sensitivity were augmented enough to induce hunting, the frequency would be of the order of 1 cycle per sec. In the fifth of the Post Office thermostats, and in the N.P.L. furnace, already referred to, the designers have gone farther still. The master and slave coils are not merely in good thermal contact; they are in perfect contact, being, in fact, identical. However great the control sensitivity were made, hunting of the sort under consideration could not occur.

We proceed to examine the significance of the control sensitivity apart from its influence on the occurrence of hunting. We ignore any differences between the temperatures of master coil, chamber, and slave coil, treating them as having a uniform common temperature, which is either the actually steady temperature of the chamber, or, if hunting is present, the mean value of

the temperature during a cycle. Whether hunting is present or not, we are investigating the steady states of the whole apparatus, not the transient conditions when passing from one steady state to another. Let $\theta$ = temperature of chamber; $\phi$ = ambient temperature; $N_1(\theta - \phi)$ = power emitted from the chamber (conduction, convection, radiation), where $N_1$ is a positive constant, conveniently expressible in watts per deg. C.; $P_1$ = heating power in slave coil (i.e. controlled by the master coil); $N_2 = -\partial P_1/\partial\theta$, where $N_2$ is a positive constant, conveniently expressible in watts per millideg. ($N_2$ is a measure of what has been referred to as the control sensitivity); $P_2$ = heating power outside the slave coil; $V_1$, $V_2$ = p.d.'s. of sources supplying $P_1$ and $P_2$ respectively. We take $P_1 \propto V_1^2$, and $P_2 \propto V_2^2$.

The above symbols represent the values under the ideal normal conditions. Departures from these values are represented by $d\theta$, $d\phi$, $dP_1$, $dP_2$, $dV_1$, $dV_2$.

The equation of normal condition is

$$N_1(\theta - \phi) = P_1 + P_2 \quad . \quad . \quad . \quad . \quad (1)$$

and the equation governing departures from normal conditions is

$$N_1(d\theta - d\phi) = dP_1 + dP_2 \quad . \quad . \quad . \quad (2)$$

Now $$dP_1 = \frac{\partial P_1}{\partial\theta}d\theta + \frac{\partial P_1}{\partial V_1}dV_1 = -N_2 d\theta + 2P_1\frac{dV_1}{V_1}^*$$

and $$dP_2 = 2P_2\frac{dV_2}{V_2}$$

Hence (2) is

$$(N_1 + N_2)d\theta = N_1 d\phi + 2P_1\frac{dV_1}{V_1} + 2P_2\frac{dV_2}{V_2} \quad . \quad (3)$$

Equation (3) is available for investigating dispositions in which the heating powers $P_1$ and $P_2$ are derived from independent sources, whose fluctuations therefore need not be equal. Usually a common source will be used. For the sake of simplicity we therefore take

$$\frac{dV_1}{V_1} = \frac{dV_2}{V_2} = \frac{dV}{V}$$

Equation (3) then simplifies to

$$(N_1 + N_2)d\theta = N_1 d\phi + 2(P_1 + P_2)\frac{dV}{V} \quad . \quad . \quad (4)$$

From (4) we can read at once the magnitudes of the two basic imperfections of the apparatus, namely:—

Ambient-temperature inconstancy

$$(d\theta)_t = \frac{N_1}{N_1 + N_2}d\phi \quad . \quad . \quad . \quad . \quad (5)$$

Supply-fluctuation inconstancy

$$(d\theta)_s = \frac{2(P_1 + P_2)}{N_1 + N_2}\frac{dV}{V}$$
$$= \frac{2N_1}{N_1 + N_2}(\theta - \phi)\frac{dV}{V}, \text{ from (1)} \quad (6)$$

It is the object of the designer to make each of these unsuppressed temperature-changes as small as possible. The value of $d\phi$ is imposed by the weather; in a house in England it may be, say, $\pm$ 10 deg. C. A common practice is to reduce $d\phi$ by placing the chamber inside an enclosure whose temperature fluctuation is limited by the use of an auxiliary rough thermostat, perhaps to $\pm \frac{1}{4}$ deg. C. The value of $dV/V$ is imposed by the nature of the source, and may be, say, $\pm$ 6 per cent when the source is the public electric supply. Sometimes special steps are taken to reduce $dV/V$, as by the use of a floating battery or of neon stabilizer lamps. Whatever the causes and values of the independent variables $d\phi$ and $dV/V$, the specific effectiveness of the thermostat is appropriately measured by a figure of merit $\eta$ which is the ratio between the change of $\theta$ which would occur if there were no thermostatic control (i.e. $N_2 = 0$) and the change of $\theta$ which does occur. From (4), this is

$$\eta = \frac{[d\theta]_{N_2=0}}{d\theta}$$

$$= \frac{d\phi + \dfrac{2(P_1 + P_2)}{N_1}\dfrac{dV}{V}}{\dfrac{N_1}{N_1 + N_2}d\phi + \dfrac{2(P_1 + P_2)}{N_1 + N_2}\dfrac{dV}{V}} = \frac{N_1 + N_2}{N_1} \simeq \frac{N_2}{N_1}$$

Thus there is a single figure of merit which measures the effectiveness of the thermostat in combating change of chamber temperature, whether this is caused by changes of room temperature or by changes of supply voltage. Substituting $\eta$ in (5) and (6), we have

$$(d\theta)_t = \frac{1}{\eta}d\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$(d\theta)_s = \frac{1}{\eta}\cdot 2(\theta - \phi)\cdot\frac{dV}{V} \quad . \quad . \quad . \quad (8)$$

In the author's apparatus, $N_1 = 0{\cdot}15$ watt per deg. C. and $N_2 = 11$ watts per millideg., so that $\eta = 73\,000$. Consequently, if only the jacketed chamber with its slave and master coils were subjected to the variations $d\phi$ and $dV/V$, 10 deg. C. rise of ambient temperature would make the chamber-temperature rise $0{\cdot}14$ millideg.; and 6 per cent rise of supply voltage would make the chamber-temperature rise $0{\cdot}0016$ $(\theta - \phi)$ millideg., where $\theta$ and $\phi$ are expressed in deg. C.

Although the effectiveness of the thermostat depends only on the value of $N_1/N_2$, the designer's course is not yet obvious. With any given chamber, the value of $N_1$ is dependent only on the jacketing adopted; but what determines the practical largeness of $N_2$? $P_1$ is the output power from the translator controlled by an input signal $de$, which ultimately is the out-of-balance p.d. across a Wheatstone bridge comprising the master coil (Fig. 3); and

$$N_2 = -\frac{\partial P_1}{\partial\theta} = -\frac{\partial P_1}{\partial e}\cdot\frac{\partial e}{\partial\theta}$$

Realization of a large value of $\partial P_1/\partial e$ is controlled by all the practical considerations of cost, bulk, and so on, which beset the designer of any "power amplifier." We will assume that only the second factor, $\partial e/\partial\theta$, is dependent upon the design of the slave and master circuits. Now whatever the form of bridge and translator, the greatest realizable bridge sensitivity $\partial e/\partial\theta$

* It is assumed that the fluctuations of $V_1$ and $V_2$ are moderate.

is substantially proportional to the power fed into the master coil. The optimum disposition, in the search for sensitivity, is therefore that the master coil shall be allocated the whole of $P_2$, i.e. that there shall be no auxiliary heat supply. The greatest realizable value of $N_2$ is thus substantially proportional to $P_2$; and the greatest realizable figure of merit is got when $P_2/N_1$ is given the largest possible value.

Now $P_2$ and $N_1$ are not independent, but have the relation (1), namely

$$P_1 + P_2 = N_1(\theta - \phi)$$

And $P_1$, the slave-coil power, must not be less than $N_1(\phi_m - \phi)$, where $\phi_m$ is the highest ambient temperature: for if it were, the slave-coil power would be already zero, and the thermostat consequently impotent, before the highest ambient temperature was reached. Putting

$$P_1 = N_1(\phi_m - \phi),$$

we have
$$\frac{P_2}{N_1} = \frac{N_1(\theta - \phi) - N_1(\phi_m - \phi)}{N_1}$$
$$= \theta - \phi_m$$

We learn from this result that: (*a*) The greatest realizable figure of merit is proportional to the minimum difference between the working temperature of the chamber and the fluctuating temperature of its surroundings; and (*b*) the attainment of this figure is not dependent on the provision of good thermal insulation between the chamber and its surroundings. The advantage accruing from thorough jacketing of the chamber (i.e. from reducing $N_1$) appears to lie only in the reduction of the power which must be provided to maintain the desired chamber temperature.

It seems from the foregoing analysis that, provided a translator with the requisite output is available, the higher the temperature of the chamber the easier it is to obtain a large figure of merit $\eta$. Increasing the working temperature-difference $(\theta - \phi)$ reduces the ambient-temperature inconstancy [owing to the increase of $\eta$ in equation (7)]; and it leaves unaffected the supply-fluctuation inconstancy [since $\eta$ and $(\theta - \phi)$ in equation (8) rise together]. In the other direction, extremely close regulation of chambers working at, say, 36° C. for physiological purposes, if used in a room which may reach 25° C., is a slightly more difficult problem than is presented by a quartz-crystal chamber for which a temperature of 50° C. or more is permissible.

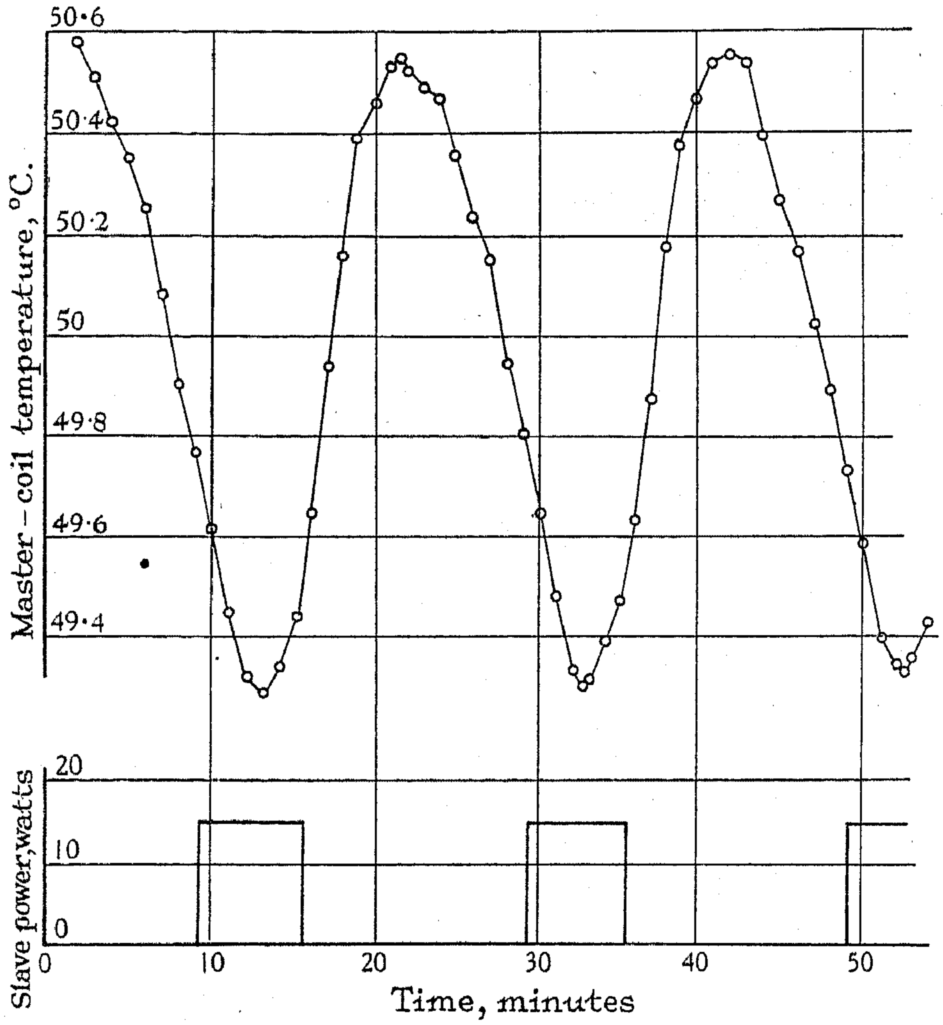



**Fig. 8.**—Hunting with relay-like control.

## (4) RELAY WORKING VERSUS AMPLIFIER WORKING

An ideal relay, devoid of backlash and set at neutral, would be as effective a translator in thermostatic apparatus as one operating with amplifier-like action and infinite sensitivity. With a real relay, the master-coil temperature must sweep over the backlash range in order to switch the slave power on and off; and the frequency of this hunting must be decreased, and its amplitude increased, if there is any thermal separation between slave and master coils. We have seen that

hunting is not necessarily a serious objection in a thermostat where even extremely fine regulation is required; consequently if, with a relay, the hunting can be given sufficiently high frequency and small amplitude, the relay may be the superior instrument. The " academic oven " has not been analysed for relay operation; but it has been examined experimentally. The translator used—which was that of the author's present apparatus—was a valve instrument which could be changed from amplifier action to relay action by the motion of a switch. In the relay disposition, and using full available control sensitivity, a slave-coil power of 15 watts was switched on and off discontinuously by a sweep of about $\frac{1}{5}$ millideg. of chamber temperature (corresponding to the backlash of the relay); while in the amplifier disposition, with the control sensitivity reduced to a value just enough to produce hunting (Fig. 5), this sweep of temperature produced a smooth change of power of about 0·0017 watt only. The hunting observed with the relay action is shown in Fig. 8. On comparing Fig. 8 with Fig. 5, it will be seen that in passing from amplifier to relay action the frequency of hunting was very little changed, and the amplitudes of master-coil temperature are of the same order in both. When the full control sensitivity was used also in the amplifier disposition, the behaviour was indistinguishable from that of the relay (Fig. 8).

In a thermostat so designed that the hunting caused with amplifier action by high control sensitivity is innocuous (high frequency and small amplitude), there is no necessity to resort to amplifier action at all. The author's present apparatus may be used in either way. No prolonged systematic test has been made with amplifier action (in which mode, as has been said, there is actually no hunting); but the author considers the relay mode preferable. The hunting frequency is about 1·3 cycles per sec., and the temperature amplitude of the master coil a fraction of a millideg.

## (5) THE TRANSLATOR

The translator, whether of relay or of amplifier type, is necessarily more or less subject to inconstancies—due to lapse of time, to ambient temperature, to supply-voltage fluctuations, and perhaps to other causes. For example, in the Post Office apparatus referred to on page 401, and in the apparatus at the National Physical Laboratory referred to on page 402, the bridge galvanometer used to deflect the beam of light on to a photocell may have a wandering zero; and the valves included in the translator are affected by voltage fluctuations; and mercury-filled valves, in particular, are affected by ambient temperature. Obviously the designer will take pains to make his translator as constant as he can; but there must be residual inconstancy; and, whether the translator is operating with relay action or with amplifier action, this inconstancy involves a proportionate change of chamber temperature. Fluctuation or wandering in the translator is another independent variable to be added to the ambient-temperature and voltage variables whose effects on the chamber have been dealt with in Section (3). It is subject, as they are, to the thermostatic correction, the effect on the chamber temperature being inversely proportional to the control sensitivity. It may be that the presence, and large amplification, of the valve amplifier A in Fig. 3 is dictated by the existence and magnitude of the inconstancies in the translator T.

## (6) THE CHAMBER AND THE MASTER COIL

Aberrations from ideal conditions must also occur in the bridge circuit containing the master coil; and these are in a different category. Here it is useless to call upon the thermostat for corrective action, and to reinforce it for its task. The slave obeys the master as obediently as ever, but the master is giving the wrong orders.*

The most obvious of these aberrations is a change of resistance in the supposedly constant arms of the bridge. If the temperature coefficient of resistance of the master coil is 0·004 per deg. C., 1 millideg. corresponds with a resistance-change of only 4 parts in a million. Now a would-be constant resistor made of, say, constantan with a coefficient $10 \times 10^{-6}$ per deg. C.† instead of zero, if exposed to an ambient change of 10 deg. C., will itself change by no less than 100 parts in a million. Used as one arm of the bridge, this would make the chamber temperature change by 25 millideg., however large the

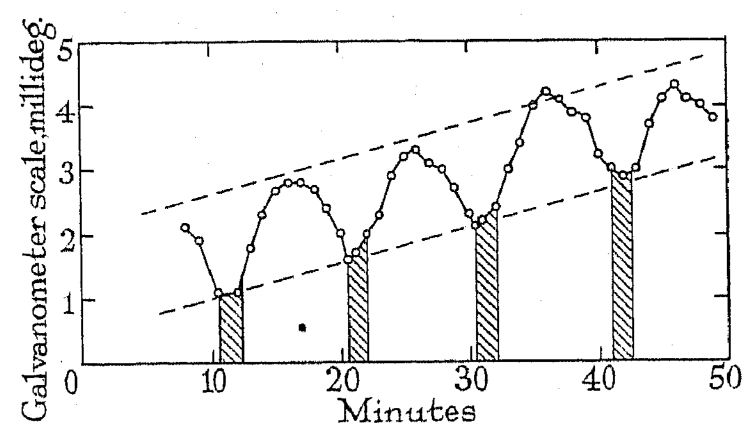



**Fig. 9.**—Effect of imperfect constancy of resistor.

control sensitivity of the thermostat. Fig. 9 well illustrates the trouble which may be experienced in such apparatus from even small changes of temperature of a would-be constant resistor. It refers to an earlier edition of the author's apparatus, when one arm of the bridge was a constantan coil located in the outer case of the isothermal chamber (Fig. 11). The temperature fluctuation of the air round this coil was quite small, perhaps $\frac{1}{4}$ deg. C. or so, but the effect on the chamber temperature is very clear. The shaded areas indicate the times when the rough-thermostat heating current was flowing. (This is the action of the bimetallic-contact thermostat seen in Fig. 11.)

The best course is clearly to provide equal ratio arms, and to arrange that any temperature-changes shall be the same in each; and (*a*) to construct the arm which balances the master coil of two mutually compensating materials or of a suitably heat-treated material, so that its temperature coefficient is exceedingly small; or (*b*) to locate this arm with the master coil itself on the isothermal chamber. The latter is an elegant solution, and presents no constructional difficulty; but it involves halving the power which can be provided in the master coil, and so

* An equivalent effect in liquid-expansion thermostats is the change of volume of the bulb with ageing, and the creep which occurs after a change of temperature.

† N.P.L. determinations have shown −40 to +10 parts in a million for samples of constantan, and + 2 to + 50 for manganin. See G. W. C. Kaye and T. H. Laby: " Physical and Chemical Constants."

halving the realizable control sensitivity, as explained in Section (3).

The effect of leakage conductance must also be borne in mind. A leak of 10 MΩ across a 40-ohm arm of the bridge would change the resistance by 4 parts in a million, and so change the temperature by 1 millideg. This suggests that the master coil should be given a low resistance.

Fluctuation of voltage of the source supplying the bridge presents an interesting problem. Since power is fed to the master coil—which power should be as large as possible to facilitate the provision of large control sensitivity—the coil must be hotter than its surroundings. This would not matter if the temperature-difference were constant; but the difference is proportional to the square of the supply voltage. Hence even though the thermostat keep the master coil at a constant temperature, the temperature of the chamber on which it is wound cannot remain unchanged when the supply voltage changes. In the author's plans, this temperature-difference effect was at first overlooked: in view of the embedding and cementing of the master coil within the wall of the chamber, it was carelessly supposed that any variation in the temperature-difference between them could be ignored. It is not so. The actual temperature-difference is found to be about 200 millideg.; and this must change by 4 millideg. for every 1 per cent change of supply voltage. On a reconstruction of the chamber, no doubt the effect could be somewhat reduced by winding the master coil of a longer, thicker wire, thus increasing the area of thermal contact with the chamber: but it could be eliminated only by making the isothermal chamber itself the master coil, which seems quite impracticable. It is thought that in any form of mains-operated apparatus, neglect to compensate for the temperature-difference effect, or rigorously to suppress fluctuations of supply voltage, must result in temperature aberrations of at least several millideg.

Identification of the slave coil with the master coil (as in Mr. Dixon's "thermautostat," and the N.P.L. furnace) only exaggerates the temperature-difference effect. In such an arrangement the temperature of the master coil is made to control the current fed to the bridge itself. Decrease of ambient temperature produces increase of current in the bridge, and therefore increase in the excess of coil temperature over chamber temperature. Thus fall of ambient temperature, and rise of supply voltage, severally depress the chamber temperature; and there seems to be no possibility, by adjustment of the thermostat-control sensitivity, of overcoming these effects.

In apparatus where the bridge is fed with alternating current (as in the author's), or with unidirectional pulses obtained from a rectifier (again as in Mr. Dixon's "thermautostat," and the N.P.L. furnace), it is not sufficient to produce a resistance balance. The bridge resistors will, presumably, be designed to be as non-reactive as can be contrived; but residual reactances, inductive and capacitive, cannot be avoided. Now any residual out-of-balance p.d., whether of the fundamental or the harmonic frequencies, which is still present when the temperature of the chamber is that which produces resistance balance, will in general affect the translator and the slave coil; and this residue will not be constant unless the bridge supply is constant in magnitude and wave-form.

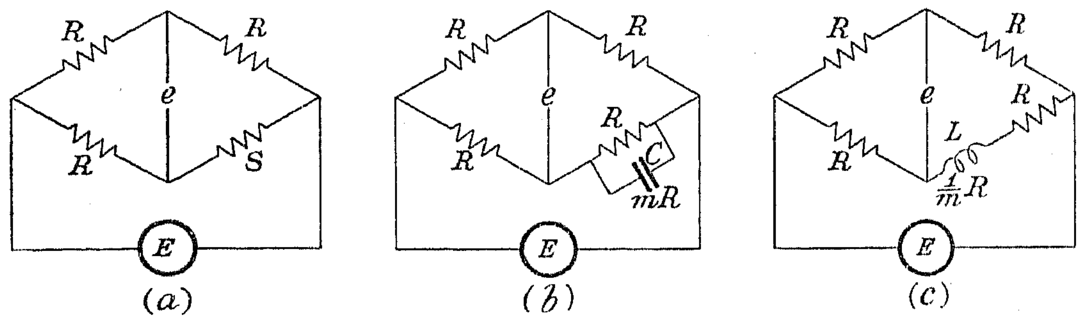



**Fig. 10.**—Slightly unbalanced bridges.

(a) $\frac{e}{E} = \frac{S - R}{2(S + R)}$ (b) $\frac{e}{E} \simeq -\sqrt{(-1)}\frac{1}{4m}$ (c) $\frac{e}{E} \simeq \sqrt{(-1)}\frac{1}{4m}$

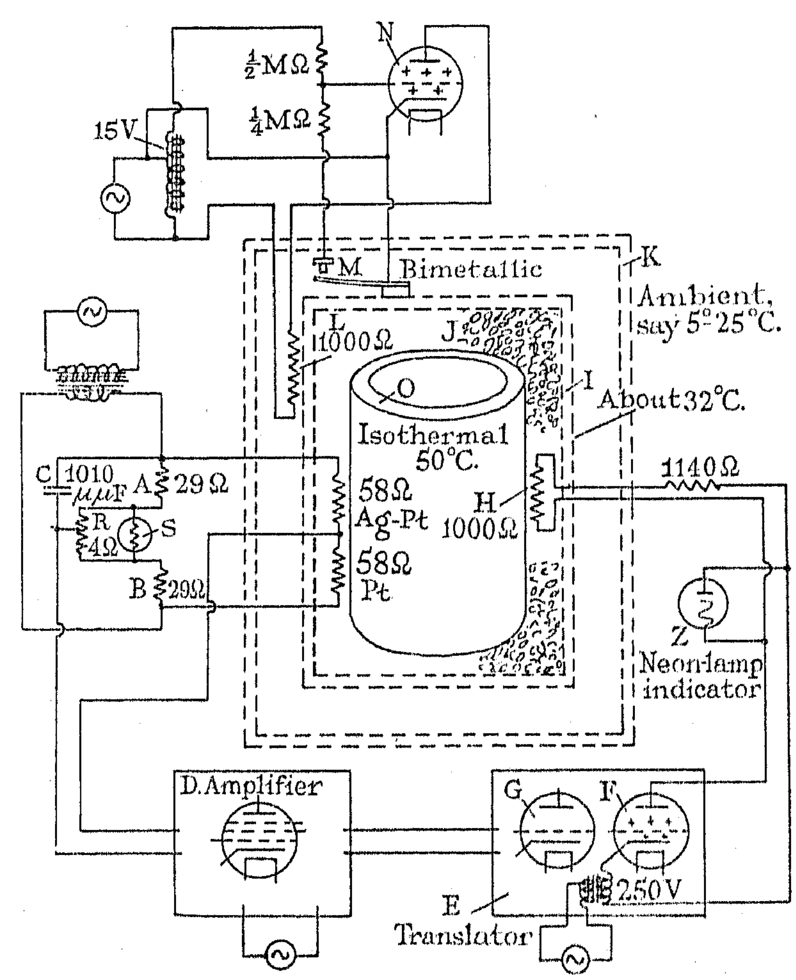



**Fig. 11.**—Skeleton diagram of author's apparatus.

(~) = Mains, 200 volts, 50 cycles per sec.
S = Compensating lamp, tungsten, rated 6 volts × 0·06 amp.

An idea of the significance of stray reactance in this respect is obtained on putting numerical values in the three bridges shown in Fig. 10. The formulae give the output p.d. on open circuit when the balance is slightly upset in the three manners indicated. $C$ is a stray capacitance of large reactance $mR$, and $L$ is a stray inductance of small reactance $\frac{1}{m}R$. In case (a) if $S$ differs from $R$ by 4 parts in $10^6$ (e.g. owing to 1 millideg. change of temperature) the value of $e/E$ is $10^{-6}$. For a frequency of 50 cycles per sec., if $R = 40$ ohms the same magnitude $|e/E|$ is given in case (b) when $C = 320\ \mu\mu$F, and in (c) when $L = 0 \cdot 51\ \mu$H. For harmonic frequencies the difficulty of obtaining a good balance is, of course, accentuated.*

of the Wheatstone bridge, whose other two arms consist mainly of the two resistors A, B marked " 29 ohms." These two fixed resistors are of constantan, No. 28 S.W.G., d.c.c., wound, interspaced, on a copper tube of diameter 1 in. Their resistances are nearly equal, and retain a constant ratio despite changes in their common temperature. The tube on which they are wound is mounted vertically in the open air. All resistors are constructed to be as non-inductive as possible; and the bridge is reactance-balanced (for the fundamental frequency) by the condenser C marked " 1 010 $\mu\mu$F."

Out-of-balance p.d. from the bridge is led, via the valve amplifier D, to the translator E, which comprises a gasfilled output valve F controlled by a vacuous input valve G. The output from the translator is alternately

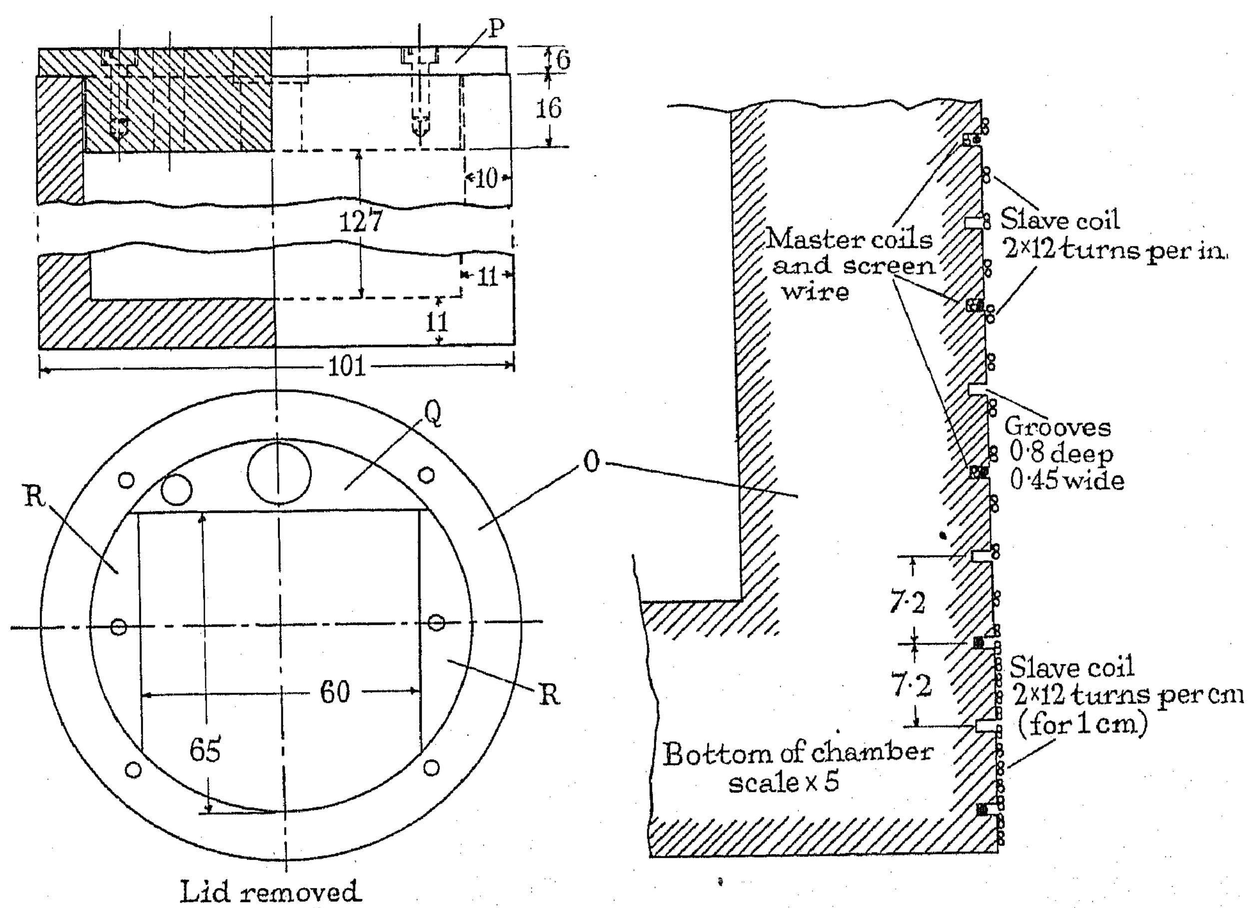



**Fig. 12.**—Isothermal chamber and its windings. (Dimensions given in millimetres.)

### (7) THE AUTHOR'S APPARATUS

A skeleton diagram of the whole apparatus is shown in Fig. 11, and is largely self-explanatory. The isothermal chamber O is an aluminium-alloy pot, with the upper end removable to form a lid. Two resistors marked " 58 ohms " lie in a helical groove cut in its external surface: one is of platinum, with temperature coefficient of resistance $0 \cdot 00327_0$ per deg. C., and the other is of silver-platinum alloy (2 : 1), of temperature coefficient $0 \cdot 00024_5$. The resistances are almost equal at the working temperature of the chamber, which is about 50° C.; but their ratio changes 3·03 parts in a million per millideg. change of chamber temperature. Together they are the temperature-sensitive element of the thermostat, the "master coil"; and they form two arms

nearly nothing (when the chamber is too hot), or the half sine-waves of current from the gasfilled valve (when the chamber is too cold). The current passes through the 1 000-ohm slave coil H, which is wound non-inductively around the chamber and the master coils.

The chamber is housed in a cylindrical canister I of diameter 7 in., with an insulating packing J about $1\frac{1}{4}$ in. thick of Chance's glass silk supplemented by celotex. The presence of this jacket divides the heat emission from the chamber by 4 or 5. The canister is fixed in a wood case K, and has a heating coil L wound non-inductively upon it. Intermittent heating of this coil, under the control of a simple bimetallic-strip contactor M* and a gasfilled valve N, holds the temperature of the canister at about $(32 \pm \frac{1}{2})$° C. whatever the ambient temperature between the limits 5° C. and 25° C. The gasfilled valve N ignites only when the bimetallic contact is closed.

* This seems to be another serious objection to the " thermautostat " apparatus to which reference has already been made. There the supply $E$ is taken from the anode of a gasfilled valve, and the method of control is such that the instant of striking depends on the heat required by the chamber, i.e. on the ambient temperature. Harmonics in the bridge current must not only be very pronounced but must vary with the ambient temperature.

* This is the only contactor in the outfit. It has required no attention from the start doubtless owing to its minute load—say, 15 volts across 0·5 megohm.

The chamber (Fig. 12) is a cast aluminium-alloy* pot O, with well-fitting removable lid P. There is an internal projection Q drilled to accommodate the bulbs of coarse and fine mercury thermometers; and there are two bosses R, with milled upper faces, on to which the

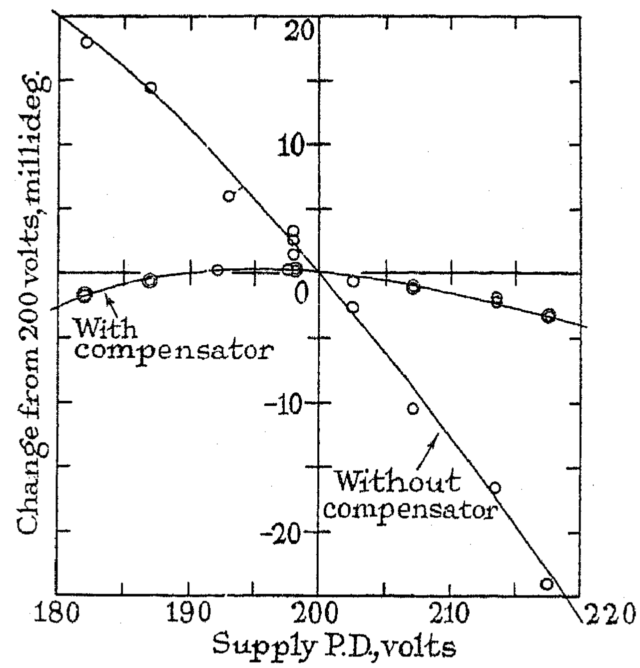



**Fig. 13.**—Effect of compensator for mains fluctuation.

mount of a quartz crystal can be screwed. The master coils, of platinum, No. 40 S.W.G., double silk-covered, and of silver-platinum alloy (2 : 1), No. 36 S.W.G., double silk-covered, lie together at the bottom of a long, and the silver-platinum 527 cm., which proportions give approximate equality of resistance at 50° C. The free ends of the wires are at the top, and their junction near the bottom, end of the winding. All connections are of copper wire, No. 22 S.W.G., sheathed in insulating sleeving and laid, before the winding was put on, in a longitudinal slot 1·5 mm. wide and 2·5 mm. deep, milled along the whole length of the outside surface of the cylinder. The connections are silver-soldered, are accommodated in shallow holes drilled in the cylinder wall, and are set solid therein with Durofix. After a thorough treatment with shellac varnish to fill the grooves, the slave coil was laid on. This consists of a non-inductive (bifilar) winding of constantan, No. 36 S.W.G., double cotton-covered, wound over the whole length of the chamber. There is some concentration of the slave coil near each end of the winding to compensate as far as possible for the lack of heat supply over the flat ends of the chamber. Finally, the slave coil was liberally varnished, and was wrapped with tape. After prolonged baking, the insulation resistances between windings and chamber at 65° C. were found to be: master coil, 10 000 MΩ; slave coil, 400 MΩ. At 50 cycles per sec. the effective inductance of the whole Pt/Ag-Pt loop was found to be within $\pm$ 0·2 $\mu$H of zero.*

The alternate empty slots seen in Fig. 12 are actually occupied by an exact duplicate of the master coils. This is used as the temperature-sensitive arms of a bridge constituting an electric thermometer, which is an alternative to the mercury thermometer.

Compensation for the overall effect of change of mains

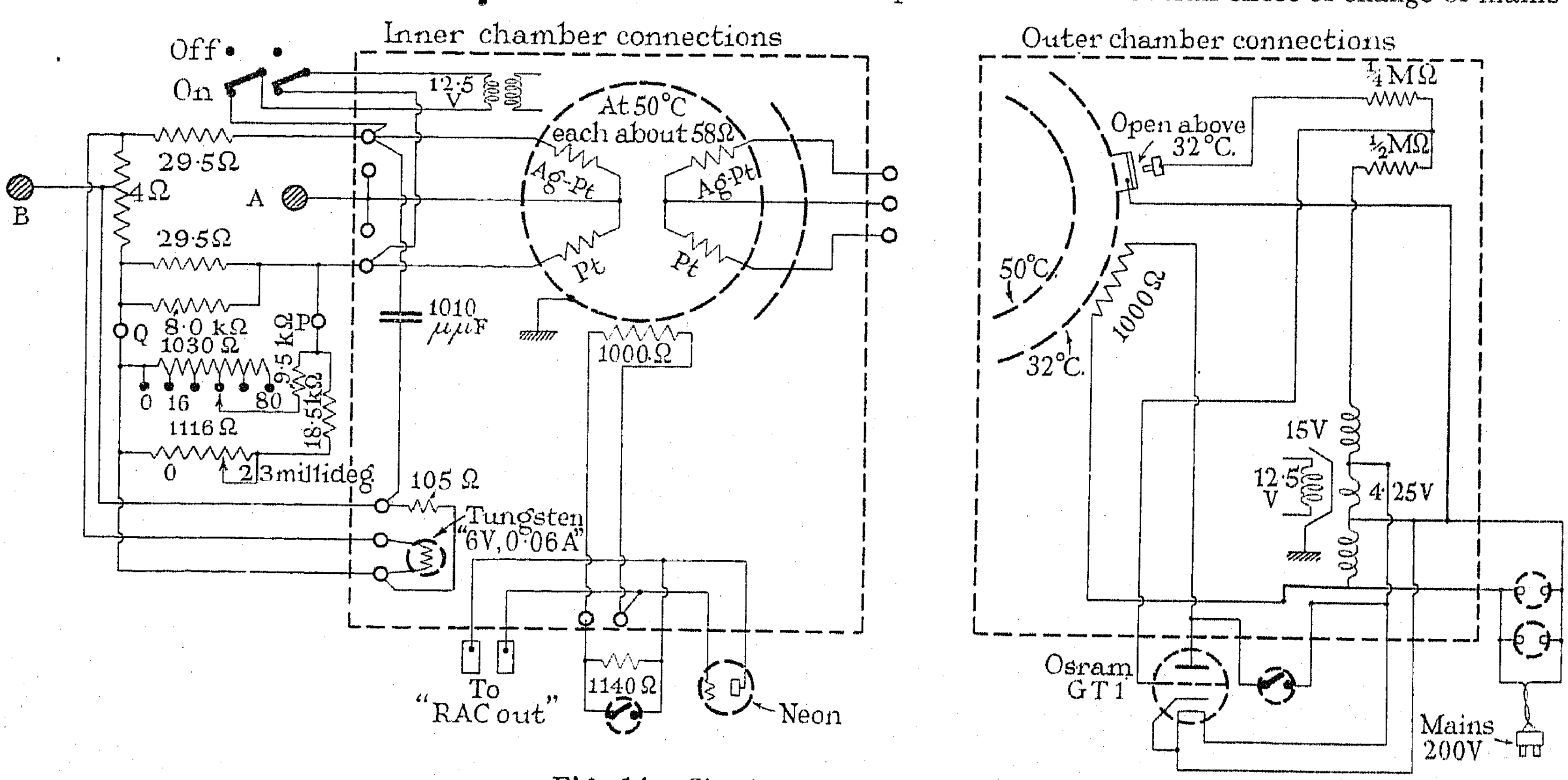



**Fig. 14.**—Circuits of chamber box.
Terminals A, B, connected to "RAC in" via amplifier. Earthed screens not shown.

helical groove, and are screened by a copper covering wire of No. 30 S.W.G. connected to the chamber and to earth. The master coils extend over the middle 12 cm. of the cylinder. The platinum wire is about 561 cm.

voltage—the chief component of which is the temperature-difference between chamber and master coil—is provided by the vacuous tungsten lamp S (Fig. 11). The resistance

* Thermal conductivity 0·296, density 2·85, specific heat 0·203, calorie-gramme-cm.-sec. units.

* Measurement of an earlier chamber of generally like construction shows that if this winding had been a loop of nickel, No. 40 S.W.G., double silk-covered, the inductance would have been about 9 $\mu$H with 10 volts applied, and 8 $\mu$H with 3 volts. The magnetic property of the nickel is very perceptible.

of the lamp varies with the p.d. across it, and hardly at all with the ambient temperature of its surroundings.* At the working p.d., about 0·8 volt, the resistance is 38 ohms, changing at the rate of 0·2 ohm per 1 per cent

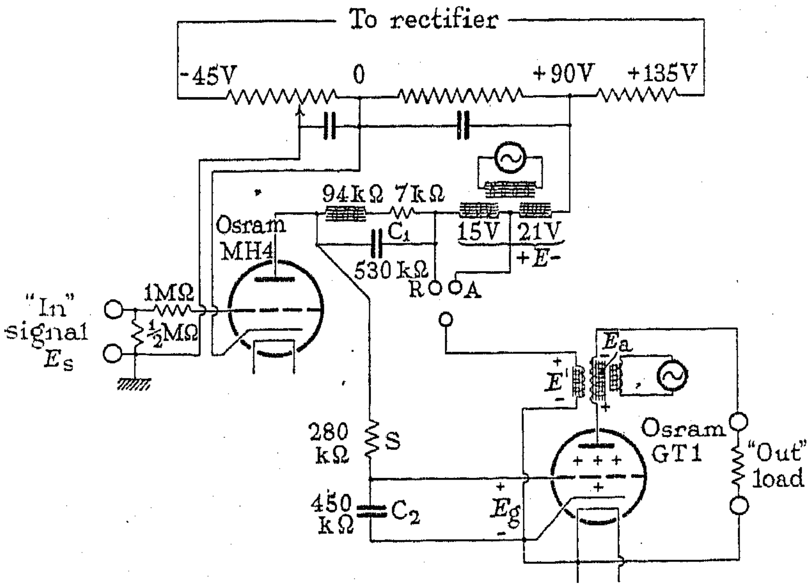



**Fig. 15.**—Skeleton diagram of translator.

change in p.d. The farther the tap on the shunt R is moved from the mid-point, the more rapidly does the bridge-arm ratio change with change of supply p.d. The correct point was, of course, determined empirically; it is about 0·05 ohm away from the mid-point. Fig. 13 shows the observed relation between mains p.d. and chamber temperature before and after this compensating device was fitted.

The most favourable bridge-arm ratio to adopt is unity, and the master coils were constructed to have this ratio at the selected working temperature. But the working temperature can, of course, readily be changed by shunting one of the arms of the bridge. Any large change

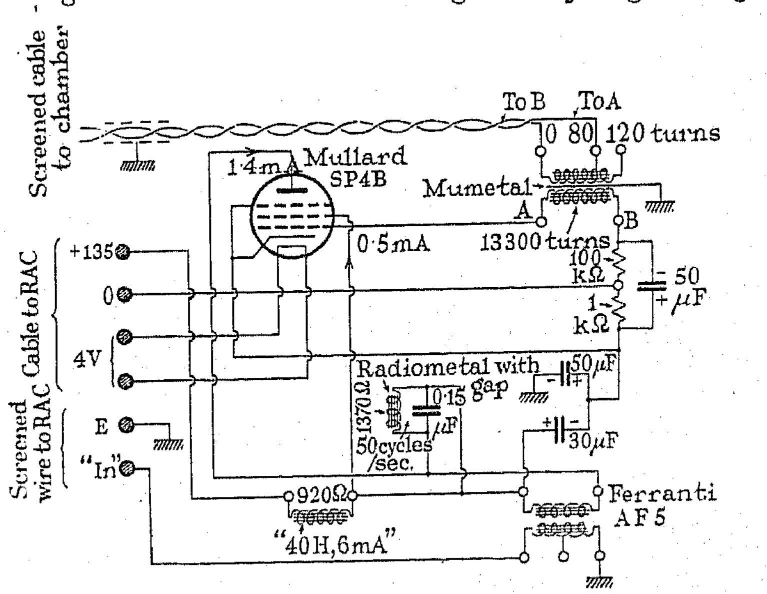



**Fig. 16.**—Circuits of valve amplifier. (Overall sensitivity, oven to RAC, 0·28 volt per millideg.)

would call for readjustment of the lamp compensator, but for a small change this is unnecessary. Easy adjustment of working temperature through a range of 103 millideg. is provided for by an adjustable shunt (T in Fig. 20) across the lower 29-ohm arm. Changes are made in steps of 16 millideg. by a plug and six sockets, and any intermediate temperature is obtainable by a sliding rheostat which is scaled in 1-millideg. divisions and has a range of 23 millideg. Details of these and all other circuits belonging to the chamber box can be seen in Fig. 14.

The box of apparatus used here as the translator is actually a comprehensive instrument, capable of such various functions that no single descriptive name has been found for it. It is perforce referred to as "RAC" (relay-amplifier-compensator), and is fully described elsewhere.* The principal components used in its present application are shown in Fig. 15, which is reproduced from the paper referred to. When a signal—which may be of d.c. character or, as in the present instance, of mains frequency—is applied at the "In" terminals, it modifies the phase of the grid excitation

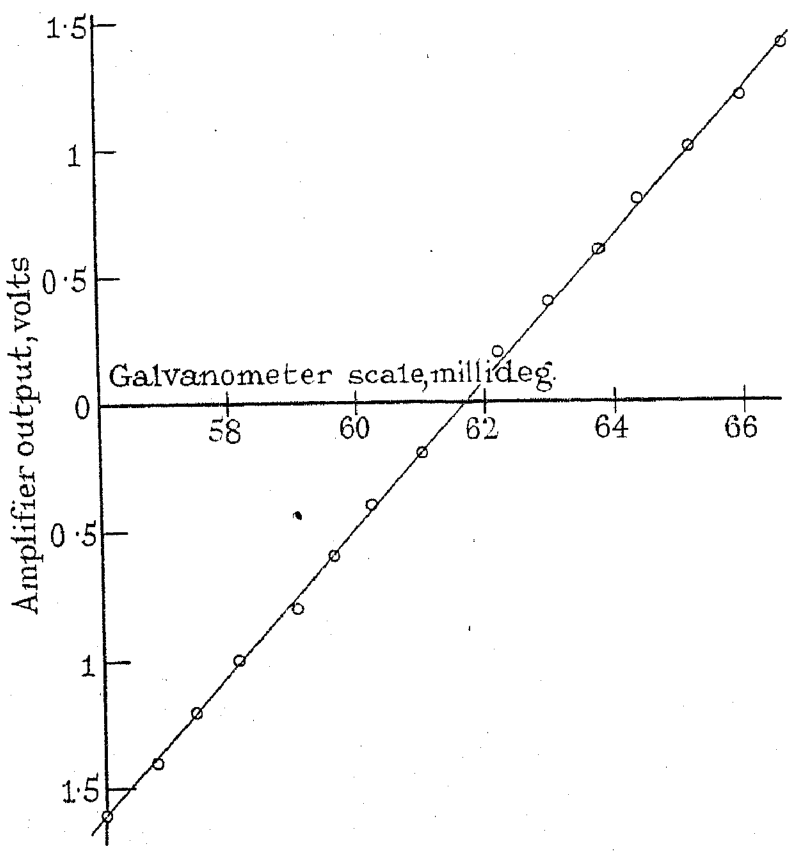



**Fig. 17.**—Temperature sensitivity of bridge-cum-amplifier. (Slope of line drawn = 0·28 volt per millideg.)

of the gasfilled output triode on the right. According to whether the 2-way switch is at R or at A, the output current is switched on and off (i.e. in relay fashion), or is continuously controlled in proportion to the strength of the input signal (i.e. in amplifier fashion). The results quoted in this paper refer to the relay mode of operation, which is preferred. In the present use the relay is set at neutral by a potential-divider knob (U in Fig. 20), which adjusts the grid bias of the input valve. The relay threshold is made insensitive to change of mains voltage by the use of a baretter which partially shields the heater of the input valve. The instrument is fed wholly by a connection to the a.c. mains; and it includes terminals from which supplies may be taken to other apparatus. In the present application of RAC as the translator, the amplifier between it and the bridge is fed entirely from these terminals. The output from the translator is in the form of unidirectional pulses of current at the mains frequency.

* See the author's remarks on the p.d./resistance relation of tungsten lamps, *Journal I.E.E.*, 1936, vol. 78, p. 529.

* L. B. TURNER: *Wireless Engineer*, 1937, vol. 14, p. 229.

The details of the amplifier are shown in Fig. 16. The amplification is large; when the amplifier is connected in circuit the ratio between the output and input p.d's. is 10 300. Since the amplifier supplies are derived from the mains, and the signal is itself of mains frequency, careful attention to smoothing and screening has been necessary. The rejector circuit which shunts the output transformer serves to attenuate mains harmonics, the unbalanced residuum from the bridge. At its resonant frequency, approximately 50 cycles per sec., its impedance is about 110 kΩ, and for the third and fifth harmonics about 5 kΩ and 3 kΩ. It is actually tuned to a frequency slightly above 50 cycles per sec. in order to adjust the phase of the input signal to the translator. The observed relation between chamber temperature and input signal at the translator is given in Fig. 17.

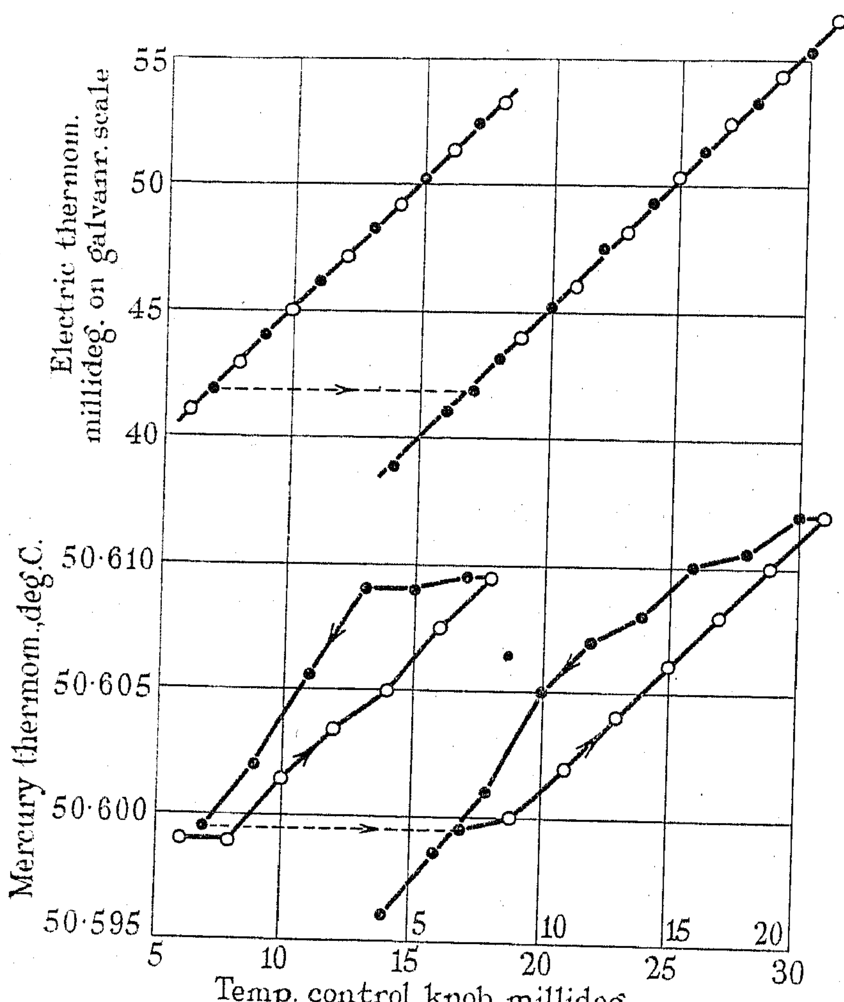



**Fig. 18.**—"Sticking" of mercury thermometer.
Points ○, increasing.
Points ●, decreasing.

## (8) MEASUREMENT OF CHAMBER TEMPERATURE

Any bald statement of long-time temperature-changes of the order of 1 millideg. is not to be made lightheartedly, and it may properly provoke the response: The temperature of what body do you claim to have measured, and how did you measure it?

In the present apparatus a mercury thermometer (V in Fig. 20), with its bulb embedded in the thickened wall of the chamber, would, if its readings could be accepted as a true indication of the temperature of the bulb, have served perfectly for indicating fluctuations of the chamber temperature as small as a fraction of a millideg. (and on the same instrument as large as 1 000 millideg.). It was hoped that this so simple indicator would suffice, and in the first chamber constructed no other was at first provided. A Beckmann thermometer of range 5·2 deg. C., graduated in hundredths of a degree (0·44 mm.), appeared to be fairly satisfactory, except that it was too coarse an instrument. A similar make of thermometer of range 1·1 deg. C., graduated in five-hundredths of a degree (0·22 mm.), which was the best example of several tried, exhibited marked "sticking"; at the same temperature upward and downward readings might differ by 10 or even 20 millideg. Most of the sticking was removable by the application of a rather violent vibrator (electric buzzer, W in Fig. 20) bearing on the top end of the thermometer; but it was found that even so a stationary reading was no proof of constant temperature. This was not due to barometric effect (which was found to be 1·3 millideg. per 1 cm of barometer). The residual sticking was such that small temperature-changes could be ascertained with this five-hundredth-degree thermometer even rather less exactly than with the coarser hundredth-degree instrument.

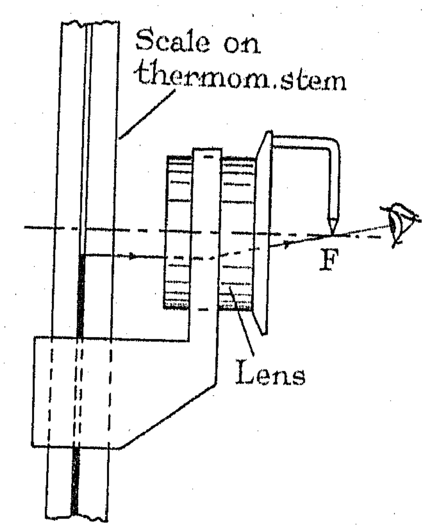



**Fig. 19.**—Anti-parallax device.

A thermometer of very similar dimensions to the last, of fixed range 50°–51·1° C., graduated in five-hundredths of a degree (0·24 mm.) was then obtained.* This shows much less of the sticking which is removable by vibration; but when the temperature is made to rise and fall through a small range a backlash amounting to as much as 5 millideg. is sometimes observable (despite use of the vibrator). Its behaviour is illustrated in Fig. 18, where two consecutive up-and-down excursions of temperature are graphed. In this test ample time (2 minutes) after each change was allowed, and the thermometer was vibrated, before the reading was taken.

In the light of this experience it is thought that, where changes of the order of 1 millideg. are significant, with any mercury thermometer a stationary reading should not be taken to indicate a constant temperature. In the author's tests, therefore, in reading the chamber temperature from the mercury thermometer the following routine has been consistently observed. The regulator knob is turned back 8 millideg., and left until the mercury falls; the knob is then restored to its former setting; after a wait of 2 minutes or more the thermometer is vibrated and its reading is taken. Six readings made

* Made by Messrs. Short and Mason. The Beckmann thermometers were of German manufacture.

in this way in rapid succession—i.e. during a period of about 20 minutes—were as follows: $50 \cdot 609_0$, $50 \cdot 609_5$, $50 \cdot 609_5$, $50 \cdot 610_0$, $50 \cdot 609_5$, $50 \cdot 609_5$, degrees C. With this procedure, therefore, it seems that short-time thermometer aberrations are reduced to a fraction of 1 millideg. (But of course such procedure would not be permissible if the chamber were in actual use in the way intended, viz. for holding its contents at a fixed temperature.)

Another, and a well-known, troublesome phenomenon in mercury thermometers is the "soaking" effect. If the thermometer is left at room temperature for a time, on returning to 50° C. it rises too high, and subsequently very slowly sinks. Several days must elapse before the thermometer is again in a condition truly to indicate small long-time changes of temperature.

The fine scale of the thermometer is easily read—to the nearest millideg.—with the help of the simple anti-parallax device shown in Fig. 19.* The wire point F is fixed rigidly at the focus of the lens. Consequently, on aligning it with the mercury surface, the ray entering the eye must have traversed the scale in a standard direction, namely parallel to the axis of the lens. A barometric correction (about $-1$ millideg. per cm. rise) is required. The bulb of the thermometer, which is about 80 mm. long and 11 mm. in diameter, is located in the longitudinal middle of the chamber. So far as aberrations of glass and mercury permit, it measures the mean temperature of the chamber over this portion of its length.

An independent measure of temperature-change is obtained from the duplicate Pt/Ag-Pt winding on the chamber, which is connected to form two arms of a Wheatstone bridge, with battery and galvanometer. The scale can be read to within $\frac{1}{4}$ millideg., and to that accuracy now gives indubitable indication of short-time changes in the mean temperature of the middle 12 cm. of the chamber. Long-time measurements are, of course, subject to any slow changes in resistance of the arms of the bridge. No investigation of bridge constancy has been made, and it is hard to see how any direct test could be made. After prolonged use in standard conditions, its constancy over a term of weeks may be fairly safely presumed.

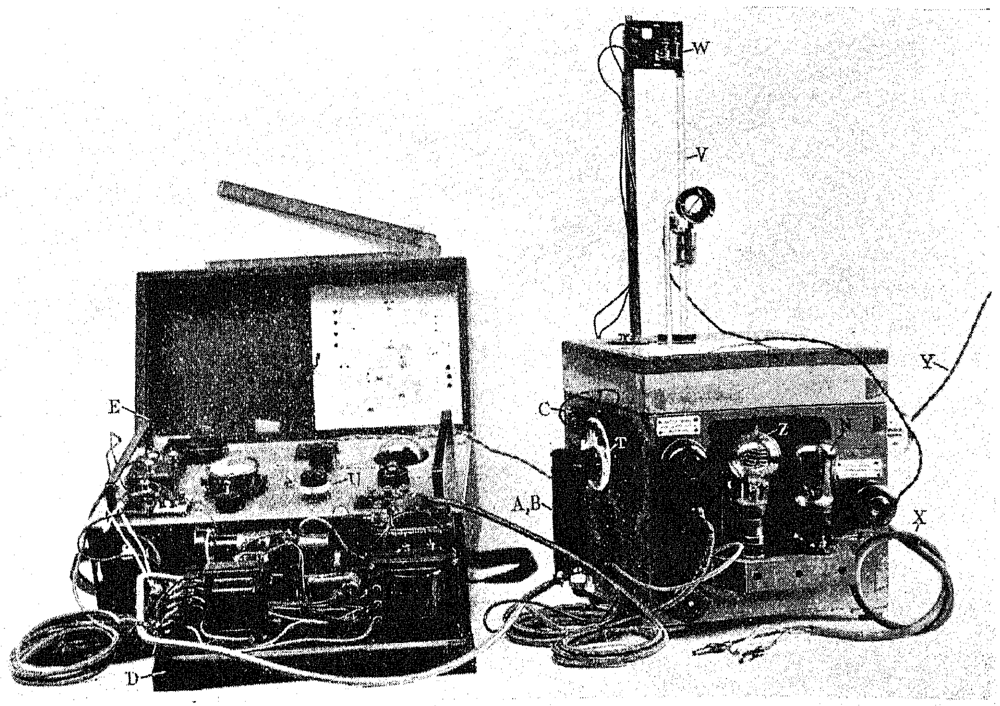



**Fig. 20.**—Complete outfit.

## (9) PERFORMANCE

Fig. 20 is a photograph of the complete outfit, excepting the ratio box and galvanometer forming the electric thermometer, to which connection is made through the 3-core cable X. The index letters in Fig. 20 agree with those in Fig. 11. The sole electric supply is taken from the mains through the flexible cable Y, which runs off the picture. Although the apparatus was in fact worked when posed for the photograph, such closeness of the three parts is dangerous on account of possible interaction caused by stray transformer fields. The three components are connected together by the screened flexible cables visible, and may be spaced as found convenient.

A prolonged test, lasting nearly 2 weeks, is graphed in Fig. 21. During the test no adjustments were made to any part of the apparatus, with the following exceptions: (*a*) After each reading of the electric thermometer, for reading the mercury thermometer the temperature regulator was shifted through 8 millideg. and restored in the manner described in the last section. (*b*) In order to

* Suggested by the author's son, Mr. K. W. Turner.

exaggerate the change of supply p.d., shortly before abscissa numbers 16 and 18 on the graph a tap on the supply transformer was shifted (and so left) whereby the supply p.d. was changed by + 10 volts and − 20 volts respectively.

The full-line graph A shows the mercury-thermometer readings corrected for barometric changes; and the dot-dash line is ruled midway between the extremes of this graph. Fluctuations in the electric-thermometer readings (graph B) are a little wider, and cannot be correlated with the mercury fluctuations. To avoid error from thermo-junction e.m.f. and wandering zero of the galvanometer, the readings were always taken by producing balance with the ratio box, indicated by no change of deflection on reversing the supply to the electric-thermometer bridge. It should be mentioned that the reversing switch was subsequently found to be defective, sometimes giving more current in the bridge one way than the other. It is estimated that vagaries in the electric-thermometer readings (in Fig. 21) up to 1 millideg. may have been caused in this way. It is thought that the full-line graph A is likely to be a substantially accurate record of the actual temperature-changes during the test: and here departures from the dot-dash line nowhere reach ± 1 millideg.

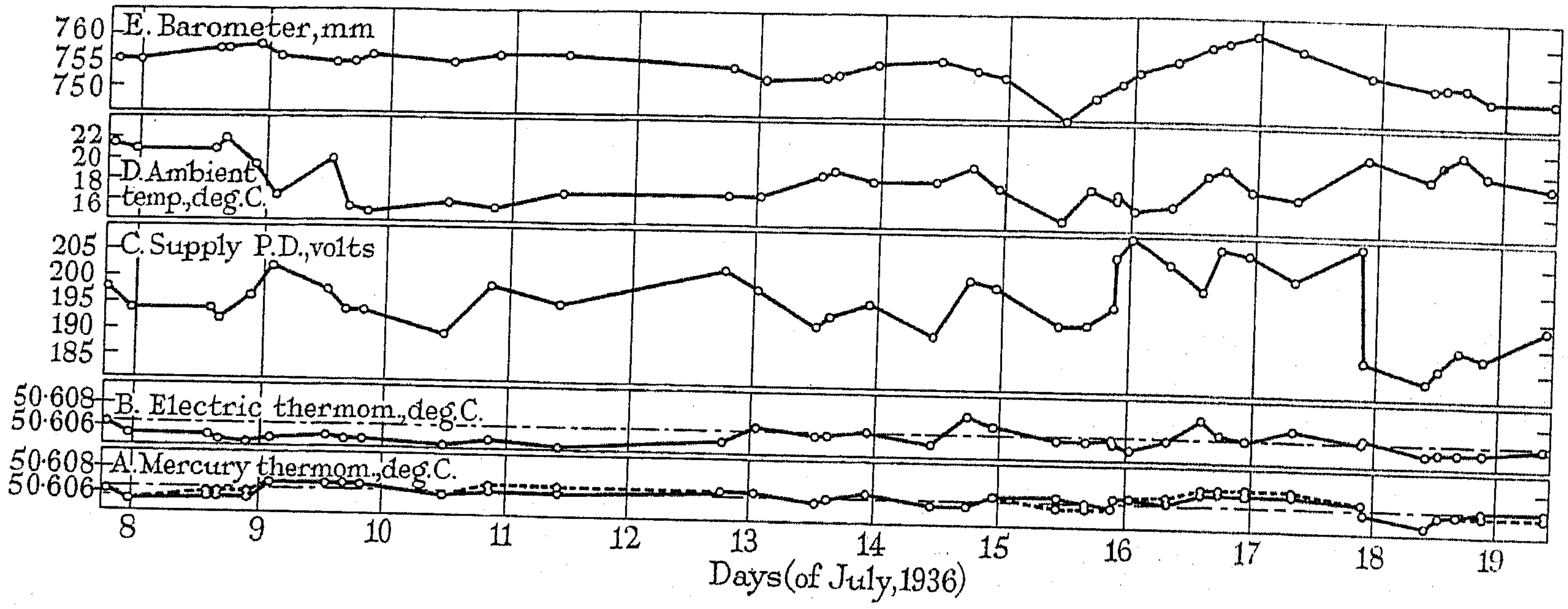



**Fig. 21.**—Record of constancy test.

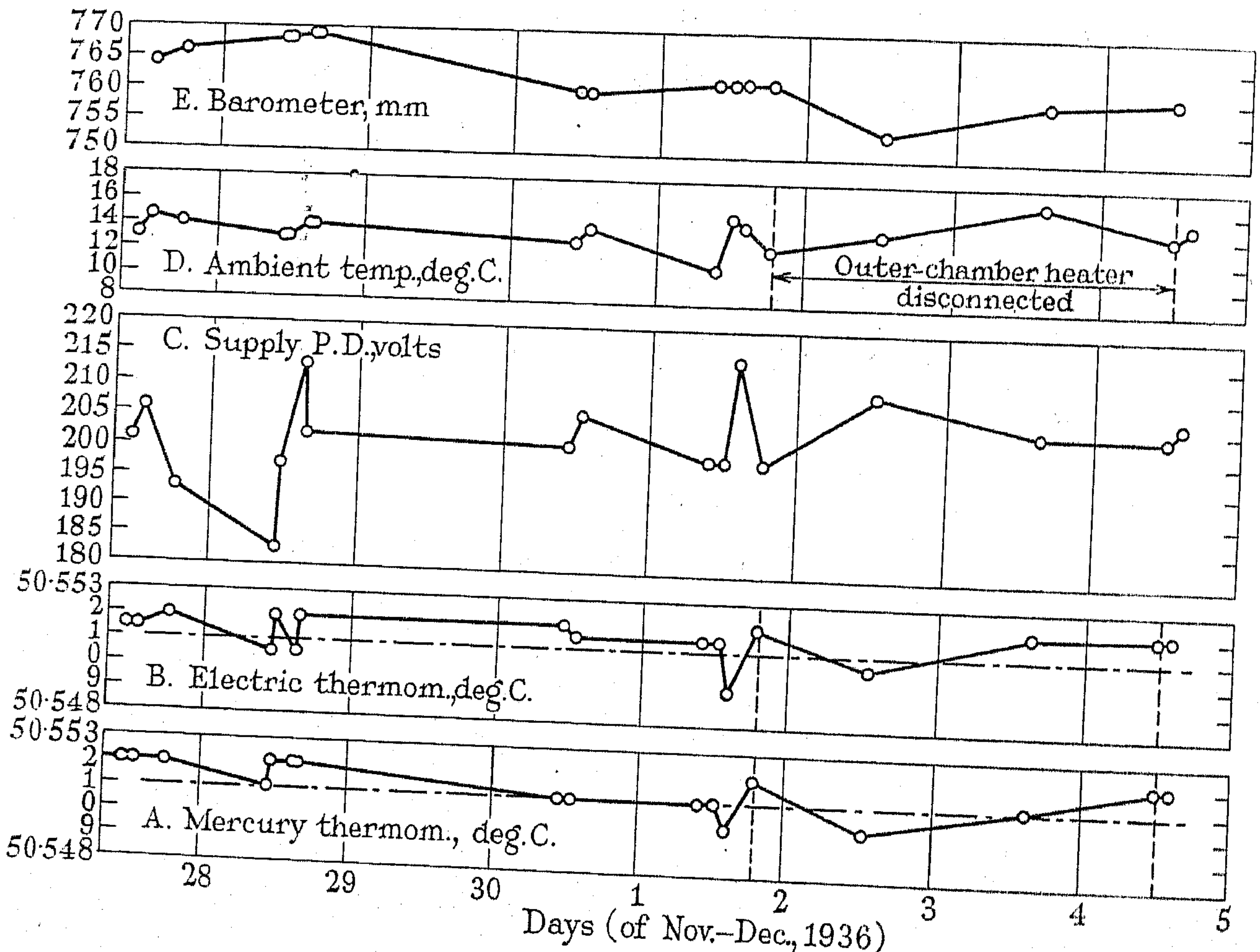



**Fig. 21A.**—Record of later constancy test.

A later test, made after the defective switch mentioned above had been replaced, is graphed in Fig. 21A.

It will be seen that graphs A and B, giving the mercury- and electric-thermometer readings, here agree better than in Fig. 21. In graph A of Fig. 21A, departures from the dot-dash line do not exceed 1 millideg., and they would be reduced on correcting for the barometric changes shown in graph E.

In Fig. 21A there were severe fluctuations of supply voltage, which varied between 183 and 215 volts. The ambient temperature did not vary much; but for some $2\frac{1}{2}$ days near the end of the run the crude thermostat control of the outer-chamber temperature was put out of action, causing the temperature there to be about

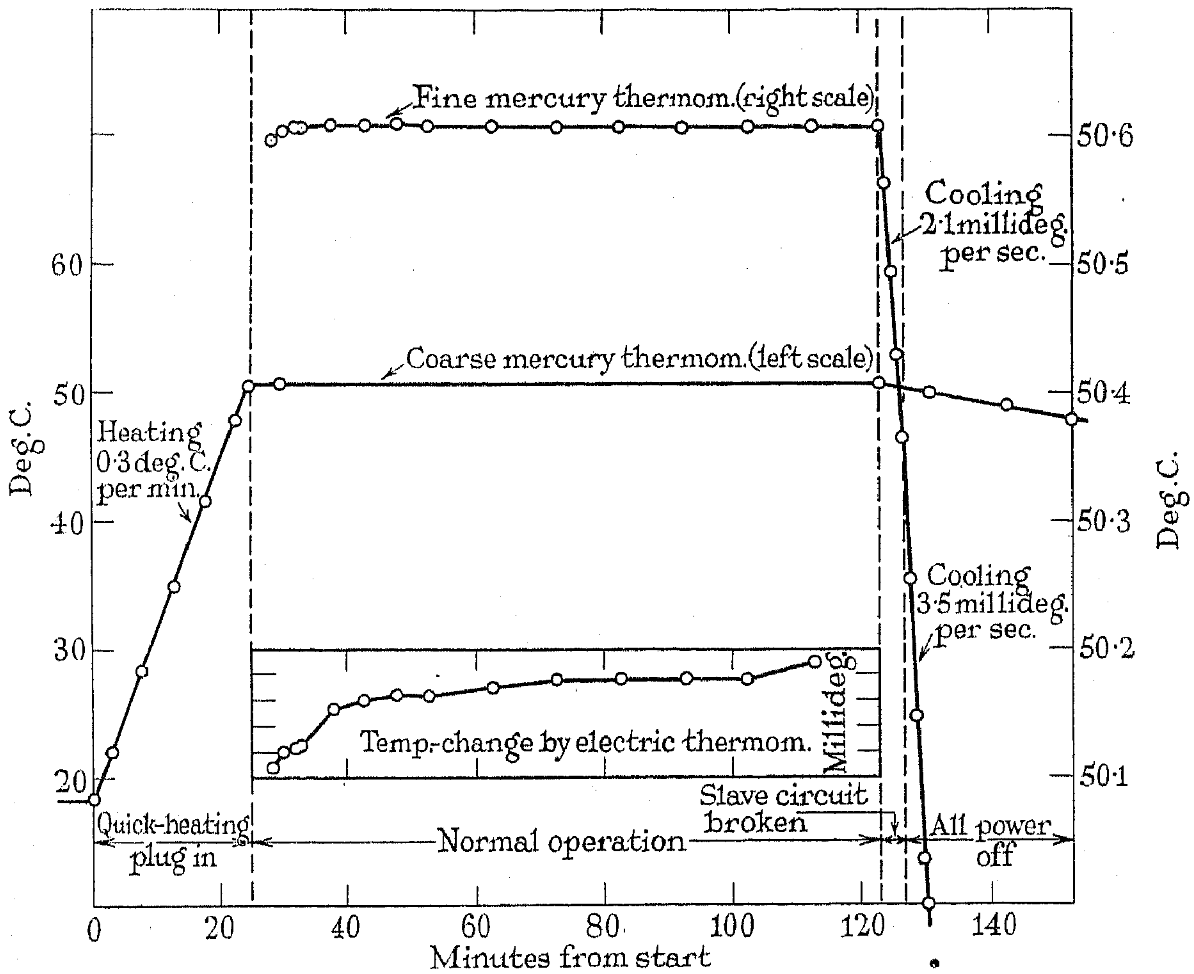



**Fig. 22.**—Starting from cold.

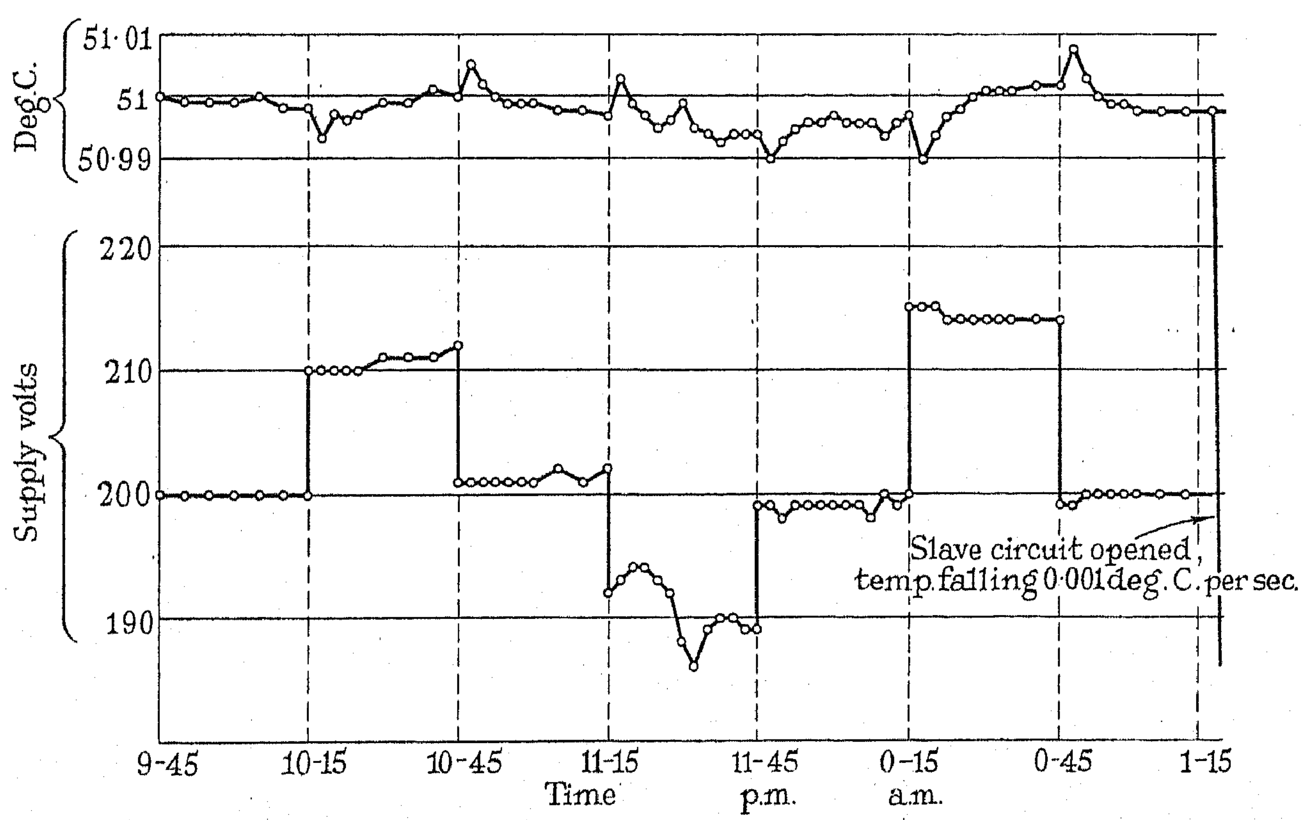



**Fig. 23.**—Performance with earlier chamber. (Readings taken every $2\frac{1}{2}$ or 5 min. Mains transformer altered every half-hour.)

24° C. instead of the normal 32° C. It will be seen that this produced no observable effect on the temperature of the inner chamber.

A feature of the chamber which might be convenient in some applications is the rapidity with which it can be started up from the cold. For quick heating, provision is made to apply the mains directly to the slave coil, which then receives 40 watts. If this is done for the initial 25 minutes or so, the chamber can be left in running condition in half an hour from the start. Fig. 22 shows such a quick start, the subsequent settlement of working temperature, and the cooling rates on switching off. The cooling rate of 2·1 millideg. per sec. when the slave circuit was broken is abnormally large because the glass silk had not yet assumed its final temperature-gradient. The normal rate (seen in Fig. 23) is about 1 millideg. per sec.

In the present chamber no provision for sealing the contents against the atmosphere (e.g. for evacuation) has been made. But the cylindrical form, with no control-circuit or temperature-measuring connections inside the chamber, is particularly amenable. A rubber gasket under the lid flange could be used.

## (10) CONCLUSION

The apparatus which has been described was constructed by the author to find out what could be done rather than to meet a known specific want. It was necessary, however, to choose some definite size and shape and temperature; and a small chamber to accommodate a single quartz oscillator was selected. There appears to be no obstacle to obtaining a like performance with widely different size and temperature, if not of shape. The power turned on and off in the present slave coil is about 5 watts. This could be increased tenfold without any alteration of the present translator. Now for a given pattern of chamber and insulating jacket, the heating power required for any specified temperature is proportional to the linear dimensions. With the present amplifier and translator, the same performance could be given with a chamber of 1 000 times the present volume. But there is no difficulty in augmenting the power indefinitely: the output from the present translator can be used, not for heating the chamber directly, but for controlling the grids of a bank of other gasfilled valves whose anode circuit delivers the heating current. This has been actually demonstrated by the author on a small scale, namely with two Osram GT1 valves delivering some 250 watts.* A chamber with linear dimensions 50 times greater than the present apparatus has an internal volume of over 2 000 cub. ft., the size of a room. If it were profitable so to do, it would be practicable to transport apples from Australia at a temperature held constant to 1 millideg. Alternatively, the higher power could be used to heat a furnace of moderate size to a high temperature; but the problem of refractory materials to replace silk, shellac, and the like, would arise.

In planning larger chambers, the cost of the platinum and silver-platinum wires would have to be considered. In the present master coils there is a total of only 3·5 g. of platinum; but in large sizes probably platinum would not be used. In a forerunner of the present chamber, nickel was used on account of its conveniently high resistivity. That chamber was defective in other respects;* but its general behaviour, of which a sample is shown in Fig. 23, suggests that if nickel had been retained any detrimental effect on the performance need not have been very serious. The author would, however, now prefer copper and constantan wound together on the chamber, eschewing nickel on account of its magnetic quality. The adoption of platinum and silver-platinum made it easier to reduce the reactance of the master coils; but with some preliminary trials to ascertain appropriate dimensions, a loop of two parallel wires of very unequal sizes, wound in grooves to form the master coils, could probably be given negligible reactance by the well-known method originally introduced by G. A. Campbell.†

## (11) ACKNOWLEDGMENTS

The author wishes to express his thanks for help received in various quarters. He is indebted to Dr. F. R. Winton for information about his thermostat; to Prof. A. V. Hill, F.R.S., and Mr. J. L. Parkinson, for showing him the apparatus in use at University College, London; to Dr. A. J. M. Smith for information about measurement of heat production as a method of investigation in plant physiology; to Dr. G. A. Tomlinson and to Dr. F. H. Schofield for showing him the apparatus at the National Physical Laboratory; to Mr. Albert Campbell, M.A., for very kindly measuring the inductances of the master coils; to Prof. C. E. Inglis, F.R.S., for experimental facilities at the Engineering Laboratory, Cambridge; and especially to the University, and to the Governing Body of King's College, for granting the "sabbatical year" during which most of the work was done.

## APPENDIX 1

### Conductivity and Diffusivity of Materials suitable for use in Construction of Isothermal Chambers

| Material | Conductivity $K$ | Diffusivity $\sigma$ |
|---|---|---|
| Silver . . . . . . | 1·01 | 1·74 |
| Copper . . . . . . | 0·92 | 1·13 |
| Aluminium . . . . | 0·48 | 0·83 |
| Brass . . . . . . | 0·20 | 0·34 |
| Zinc . . . . . . | 0·26 | 0·40 |
| Mercury . . . . . . | 0·015 | 0·033 |
| Cork (ground) . . . . | 0·00012 | 0·0017 |
| Celotex . . . . . . | 0·00011 | 0·0009 |
| Pine wood (across grain) . . | 0·00009 | 0·0007 |
| Chance's glass silk (packed 10 lb. per cub. ft.) . . | 0·00007 | 0·003 |

A more comprehensive list is given by L. R. Ingersoll and O. J. Zobel in their book "Mathematical Theory of Heat Conduction" (1913), from which many of the above figures were taken. Units are calorie, cm., sec.

* L. B. Turner: *Wireless Engineer*, 1937, vol. 14, p. 241. It was shown in operation during the reading of the present paper.

* See reference to Fig. 9 in Section (6).

† See A. Campbell and E. C. Childs: "The Measurement of Inductance, Capacitance, and Frequency" (1935), p. 117.

## APPENDIX 2

### Attenuation in Wall of Chamber

The end A of a prism AB of length $l_1$ and unit cross-sectional area undergoes a cyclic temperature-change $\theta_A = a \cos \omega t$. No heat flow occurs across the sides and the end B of the prism. What is the temperature cycle at B?

The similar problem of a semi-infinite insulated rod, i.e. continued indefinitely beyond B, is dealt with in the textbooks.* The treatment there given, modified for the terminal conditions at B, shows that if the temperature at A is written as $\theta_A = ae^{j\omega t}$ the temperature $\theta$ at a distance $x$ from A is

$$\theta = a\frac{e^{-(1+j)mx} + e^{-(1+j)m(2l_1-x)}}{1 + e^{-(1+j)2ml_1}}e^{j\omega t},$$

where $m = +\sqrt{[\omega/(2\sigma)]}$ and $j = \sqrt{(-1)}$.† $\sigma$ is the diffusivity of the material.

* See, for example, "Dictionary of Applied Physics," vol. 1, p. 467.
† Or see L. B. TURNER: "Self-oscillation in a Retroacting Thermal Conductor," *Proceedings of the Cambridge Philosophical Society*, 1936, vol. 32, p. 665.

Putting $x = l_1$, we have

$$\theta_B = \frac{2e^{-ml_1}.e^{j(\omega t - ml_1)}}{1 + e^{-(1+j)2ml_1}}$$

If $ml_1$ is large enough to make $e^{-2ml_1} << 1$, as it must be to make the temperature fluctuation considerably smaller at B than at A, the denominator in this expression can be taken as 1. Then

$$|\theta_B| \simeq |\theta_A| 2e^{-ml_1} = |\theta_A| 2e^{-\sqrt{\left(\frac{\omega}{2\sigma}\right)}l_1}$$

In applying this result to propagation through the cylinder wall (page 403), the length $l_1$ represents the thickness of the wall.

## APPENDIX 3

A summary of various fine-regulating thermostats encountered by the author, mainly in the course of writing this paper, is here given. There is no attempt at completeness. The figures tabulated in the last column must be taken as a rough indication only: such figures mean very little unless accompanied by a full statement of the conditions of test and manner of measurement.

| Apparatus | Reference on page | Contents, and working temperature | Method of control | Relay (R) or amplifier (A) | Method of heat distribution | Source of heat supply | Working inconstancy, millideg. |
|---|---|---|---|---|---|---|---|
| National Physical Laboratory | 401 | Invar-rod oscillator, 24° C. | Expansion of toluene breaks mercury contact | R | Circulating water | Mains | 5 in 2 years |
| T. Deighton, Institute of Animal Nutrition, Cambridge | 401 | Living fowl (and experimenter), 26° C. | Expansion of paraffin breaks mercury contact | R | Turbulent air | Mains | ± 10 for short time |
| F. R. Winton, University College, London | 401 | Living muscle, 36° C. | Expansion of toluene increases area of contact with mercury | A | Bubbled water | Mains and 200 - volt battery | 1 per 3 deg. C. of ambient |
| A. V. Hill, University College, London | 401 | Living muscle, 18° C. | Expansion of chloroform closes gas orifice | A | Bubbled water | Gas flame | 1 |
| Post Office (4 types) | 401 | Electric oscillators, 50° C. | Resce. bridge, galvr. needle, or mirror and photocell | R | Conduction | Mains and battery | ? |
| Post Office, E. J. C. Dixon's "thermautostat" | 402, 404, 408, 409 | Quartz crystal, 50° C. | Resce. bridge, galvr. mirror, and selenium cell* | A | Conduction | Mains | 16 per 1 deg. C. of ambient |
| National Physical Laboratory | 402, 408 | Metals, 1 000° C. | Platinum resce. bridge, galvr. mirror, and photocell* | R | Radiation | Mains | 20 000 per 1 per cent change of mains |
| Muirhead and Co. | — | Tuning fork, 35° C. | Expansion of toluene breaks mercury contact | R | Conduction | Batteries | ± 10 |
| General Radio Co., New York | — | Quartz crystal, 50° C. | Expansion of mercury breaks mercury contact† | R | Conduction | Batteries | ± 10 |
| L. B. Turner, Engineering Laboratory, Cambridge | | Quartz crystal, 50° C. | Resce. bridge and valve relay‡ | R | Conduction | Mains | ± 1 |

* Slave and master coils identical. † With surrounding chamber held at 45° ± 0·1 deg. C. ‡ With surrounding chamber held at 32° ± 0·5 deg. C.

[The discussion on this paper will be found on page 418.]

## DISCUSSION BEFORE THE WIRELESS SECTION, 5TH MAY, 1937

**Mr. E. J. C. Dixon:** In thinking of new aspects of periodic phenomena one is tempted to refer back to familiar regimes for an analogy, and in considering thermostats my temptation has been to draw an analogy between them and a source of rectified alternating current followed by a smoothing circuit. Unidirectional pulses of heat energy are applied to a conducting surface (analogous to a condenser) followed by a layer of heat-attenuating material (the choke) and a further "condenser," after which a substantially uniform temperature (unvarying e.m.f.) is achieved. The analogy is far from complete, however, and many difficulties are encountered in attempting to draw conclusions from its use; but it is interesting to note that in his thermostat the author prefers the "relay regime" to the "amplifier regime," and the analogy would suggest that the reason might be that the source of higher frequency offers less difficulties in the "smoothing circuit."

I wish to acknowledge the author's generous references to the work on this subject by Mr. Booth and myself. The tendency towards systematic examination to which he refers prompts the suggestion that the value of his paper would be enhanced by the inclusion of a more complete bibliography. Since 1929, for example, many excellent contributions to the art have been published in the *Journal of Scientific Instruments*, and in its American counterpart, the *Review of Scientific Instruments*.

In view of the author's reference to marked disagreement between our conclusions and his, I feel it is desirable to draw attention to the limitations of the work described in our paper. The author's work is an "attempt to obtain the smallest possible inconstancy consistent with the derivation of electric supplies from the a.c. mains alone," whereas our efforts were primarily directed to achieving a sufficient constancy to keep crystal oscillators within the Convention tolerance, namely ± 50 parts in a million, and to keep them there for long periods of time with a minimum of attention. To design a good thermostat for reference standards of frequency was a secondary object.

For the type of crystal in use at that time, it was only necessary to keep the temperature constant to within 1 deg. C. to ensure the required constancy of frequency, and, with the reduction in tolerance which is likely to be proposed in 1938, a constancy within 0·4 deg. C. would be sufficient. As the author hints in his Introduction, however, quartz crystals can now be cut having a temperature coefficient of less than ± 1·0 part in a million per deg. C., and in primary standards of frequency the residual coefficient of the crystal plate may be compensated for by that of the holder, to give a substantially zero coefficient for the mounted crystal. The importance of a superlative thermostat is now diminished, therefore, in the particular applications with which we were concerned. It might be of interest to remark, however, that the bimetallic and resistance-thermometer types of thermostat described in our paper are still functioning satisfactorily in commercial circuits. The bimetallic types date from 1929 and the resistance-thermometer types from 1931. Simple mercury thermometers with contacts and thermionic relays have been used since 1934 for reference frequency standards, with satisfactory results.

I am able to supplement the information given in Section (2) and Appendix 3 about the mains-operated resistance-thermometer types of apparatus by the following data:—

*Working inconstancy.*—In a test run of several days (similar to that recorded in the author's Fig. 21), no variation could be detected on a thermometer reading to 100 millideg. In laboratory experiments using a calibration of the control-coil temperature in terms of the temperature of the brass slab which was intended to be the isothermal surface (admittedly an unsound method for high accuracies), the following results were obtained for a working temperature 30 deg. C. above the ambient temperature:—

| Heater power | Heating cycle | Cooling cycle | Maximum temperature variation of control | |
|---|---|---|---|---|
| watts | minutes | minutes | millideg. | millideg. |
| 30 | 4 | 1 | − 100 | zero |
| 45 | 2·5 | 1·75 | − 100 | + 50 |

*Variation with mains voltage.*—With the same apparatus and method of measurement as above and supply from metal rectifier through rheostat, the following readings are averages of several oscillations:—

| Mains-voltage variation | Bridge voltage | Min. reading | Relay on | Relay off | Max. reading | Heating cycle On | Heating cycle Off |
|---|---|---|---|---|---|---|---|
| per cent | volts | millideg. | millideg. | millideg. | millideg. | minutes | minutes |
| − 10 | 3·6 | − 140 | − 59 | + 2·0 | + 135 | 1·5 | 2·25 |
| 0 | 4 | − 140 | − 60 | + 8·5 | + 130 | 1·75 | 2·25 |
| + 10 | 4·4 | − 139 | − 60 | + 6·0 | + 135 | 1·75 | 2·25 |

With regard to the performance of bimetallic thermostats, the author says at the end of Section (2), in reference to our Fig. 35, "one would imagine there must be a serious temperature oscillation of the brass slab on which the crystal is mounted." Some measure of this is given in Figs. 41(*b*) and 42(*b*) of the paper by Mr. Booth and myself,* which, compared with Figs. 41(*a*) and 41(*c*), reveal that the oscillation is a function of the heater power in relation to the mass of brass slab and may vary from ± 70 to ± 120 millideg. in different commercial designs.

Turning to the superlative type of thermostat exempli-

* *Journal I.E.E.*, 1935, vol. 77, p. 197.

fied by the author's apparatus, I should like to join issue with the author on his criticism of the principle of the instrument which I called the "thermautostat." (I have always regarded it as unfortunate that the invention of this device coincided roughly with the production of zero-temperature-coefficient crystals, and that for this reason its development was retarded and no accurate determination of its performance was made.) Taking first his criterion for control sensitivity $s$ [Section (2)], which is proportional to $k/l$, $l$ being the distance between the slave coil and the master coil; in the thermautostat $l$ is zero and the author states that "$l$ may be decreased without limit as the master and slave coils are brought into closer and closer thermal relation." Thus he admits that the control sensitivity may be made higher in the thermautostat than in any other device. Secondly, in Section (3) the author's theory shows that the figure of merit of a thermostat depends only on the value of $N_2/N_1$, $N_2$ being effectively the rate of heating (or "a measure of the control sensitivity") and $N_1$ the rate of heat loss. Here the difference between us seems to be that, whereas the author recommends increase of $N_2$, in our paper we recommended decrease of $N_1$. Either recommendation tends to increase the ratio $N_2/N_1$, and it appears to me that design details may be a matter of individual preference. I suggest that the performance of the author's apparatus could be equalled by the thermautostat if the same refinements in construction of the resistance arms were adopted and, possibly, a d.c. amplifier substituted for the phase-controlled gas discharge device in order to avoid errors due to harmonics of the supply frequency.

I am puzzled by the behaviour of the author's apparatus with variation of mains supply voltage, since I have always regarded the temperature of the isothermal surface as independent of voltage. In the thermautostat, as shown in our Fig. 38, one imagines that with a rise in voltage the thyratron gives less pulses of anode current and that therefore the power taken for a given difference of temperature between ambient and heater will be constant. If the apparatus to be kept at an invariable temperature is not at the isothermal surface, however, it is clear that the temperature gradient between them must be kept constant. This is a good reason for thick conducting walls and good insulation to the oven. In the author's apparatus, the variation of temperature with supply voltage is clearly demonstrated in Fig. 13, and it would seem desirable to make an attempt to solve the problem of identifying the isothermal chamber with the master coil. A step in this direction would be to wind the latter inside the isothermal chamber.

**Mr. D. A. Bell:** The author brings to our notice the extreme importance of the reactive balance. If the temperature change of resistance that we want to observe is a matter of 3 parts in a million per millideg., clearly the phase angle has to be much less than 3 parts in a million; but I should like to know whether, by the use of some form of phase control in the actual translator, rather than by the RAC instrument (which I gather depends solely on the *amplitude* of the signal from the bridge windings, since it would work equally well with direct current) one could obtain a discrimination of at least 4 : 1 against the quadrature component of the bridge output. Such an arrangement might also be helpful from the point of view of certain harmonics, but this clearly depends on the phase and order of the harmonics in question.

Since the difference in temperature between the master coil and the oven is due to the fact that the resistance bridge, unlike the conventional thermometer, is a source of power, it seems that we have to strike a compromise. If we were to reduce the bridge power very greatly, and at the same time increase the sensitivity of the amplifier and translator, this effect would be diminished, and thereby the dependence of temperature on mains voltage. On the other hand, the sensitivity of the device to stray couplings would be increased; in particular, any coupling between the slave coil and the master coil would tend to cause backlash in the relay operation.

With regard to doubt as to the necessity of applying the thermostat to crystals, for many purposes the tuning fork is still a convenient standard of frequency, since it has a very much lower frequency. A temperature coefficient of the order of 10 parts in a million is good for a tuning fork, so that it needs an extremely accurate thermostat.

There is only one small point in the paper which I do not follow, and that is the volume of the chamber which could be heated for 10 times the power used in the author's apparatus. I should have thought that the heat required, after the initial heating-up period, would be proportional to the surface of the chamber, and hence to the square of any linear dimension.

**Mr. A. J. Gill:** I agree to some extent with what Mr. Dixon said about the use of thermostats for radio transmitters. The ability to cut crystals of low temperature-coefficient has for the present removed the necessity for thermostats in normal working transmitters, though I think that with the development of the art we may still have to improve the frequency stability in years to come, and so may have to use not only low-temperature-coefficient crystals but also thermostatic control. For example, it may be necessary at some future time to work on short waves with single side-band transmission, and possibly without using a pilot channel. If this were done, it would mean that at frequencies of the order of 20 megacycles per sec. we should have to keep the frequency constant to within $\pm$ 5 cycles per sec. to ensure good quality, and that would mean a much higher degree of control than we have at the present time.

We are always trying to improve our methods of measuring frequency, and although we use temperature-controlled devices at the present time associated with frequency standards of low temperature coefficients I think that a device of the kind described in the paper would enable us to make a distinct advance in our frequency standards, whether fork-controlled or crystal-controlled. Mr. Bell mentioned 10 parts in a million as the temperature coefficient of frequency of a fork: I think he must have been referring to a steel fork, because it is possible to obtain elinvar forks with one-tenth of that frequency coefficient.

**Mr. A. H. Mumford:** It is now reasonable to supply quartz crystals having a temperature coefficient less than $\pm$ 2 parts in $10^6$ per deg. C., and less than $\pm 0\cdot 5$ in $10^6$ per deg. C. for special purposes, and this, associated with the variations occurring in the circuit associated with the

crystal, makes it unnecessary to provide at commercial transmitting stations thermostats with the degree of constancy obtained in the author's design.

What I regard, however, as the major drawback of the general type of thermostat described in this paper is the fact that if the a.c. supply fails so does the thermostat. Whilst this might be tolerated in certain cases, it cannot be when associated with frequency standards, and for this use I much prefer to have thermostats operated from local battery supplies rather than from public supply mains. In such cases it seems preferable to locate the standard and its associated thermostat in an underground chamber, having a low ambient temperature variation throughout the year of say 2 or 3 deg. C., and even then to temperature-control the chamber itself to 1 deg. C.

**Mr. P. W. Willans:** The author's device has an important bearing on the comparative merits of crystal oscillators and tuning forks as standards of frequency. Hitherto the question of temperature coefficient has been in the forefront of all such comparisons, but by the use of the author's oven as a means for controlling the temperature of a tuning fork we entirely remove this consideration from the problem and we remove it with a piece of apparatus which introduces not very many additional complexities.

From this standpoint a tuning fork will derive an advantage from its linear temperature coefficient, in that the author's oven will enable the frequency to be set without much difficulty to different values within a small range, a circumstance which may be very useful if we wish to obtain a given frequency, e.g. a round number of cycles per second, without making mechanical alterations to the tuning fork.

I should like to ask the author for further information as to the extent to which the temperature of the oven can be readily changed from one value to another by adjustment of the controlling circuit, and over what range in any practical instrument this can be done. I feel that this feature might be of great advantage in other connections as well as for constant-frequency devices.

**Mr. W. L. McPherson:** With the degree of temperature stability possessed by the author's isothermal chamber it looks as though by its use in conjunction with a "zero-temperature-coefficient" crystal we could quite easily produce an astronomical clock of an accuracy exceeding that of any such clocks so far made. There is quite a number of applications in the research world which should be facilitated by this work, which lays down general principles applicable over a large range of temperatures and volumes.

The question of the sticking of the thermometer might very well be examined as an independent item. There are many such phenomena connected with temperature which exhibit a sort of slip or hysteresis effect; as the temperature is raised the molecular structure seems to remain in one condition up to a certain point, when it suddenly changes to another. A careful study of the conditions round about this critical temperature region might yield a good deal of information.

**Mr. A. H. D. Markwick** (*communicated*): A number of experimenters, in recent years, have claimed that they have been successful in obtaining thermostatic control of various apparatus to within 1 millideg. This is, however, by no means an easy thing to do, and it is necessary to examine such claims with care. In some cases thermostatic control was obtained with toluene regulators or with similar devices depending on the thermal expansion of an organic liquid. Such liquids have a high coefficient of thermal expansion, but they are also equally sensitive to changes in barometric pressure: thus the change in volume due to a change in the barometric pressure of 1 cm. of mercury is the same as the change in volume caused by a change in temperature of 1 or 2 millideg. Similar remarks apply to a less degree to mercury regulators, and the author mentions on page 412 that mercury thermometers are also affected by changes in barometric pressure. In his case the regulating device is presumably not affected by changes in barometric pressure, but it appears that the thermal capacity of the air in his oven is probably less than that of the Beckmann thermometers and resistance thermometers used to measure the temperature. These have a considerable time-lag, whereas the thermal period of the author's oven was very short. I should like to ask whether he is sure that his instruments were sufficiently rapid in response to detect periodic variations in temperature due to the cutting in and out of the slave coil, for otherwise he can only claim to control the mean temperature.

In the author's oven the thermal capacity of the air was small in comparison with that of the walls, the temperature of which largely controlled the air temperature. In the case of water-baths and rooms it is otherwise, since the thermal capacity of the controlled medium is large, and it is essential to apply vigorous stirring to ensure uniformity of temperature. Stirring also reduces the time-lags in the regulator and in the heating coils which are cut in and out by the regulator. These time-lags are principally responsible for the hunting of the temperature normally found, and I should like to draw attention to the simple theory put forward by Lalande* in this connection. He showed that it is desirable to reduce to a minimum the time-lags in the regulator and in the heating coils. It is rather surprising to find that the author used no stirring devices, and I should like to ask whether the temperature in the oven was uniform as well as constant.

In connection with close temperature control of rooms, in which I am interested, I have found the mercury-in-glass type of regulator very successful and reliable. Recently, regulators of this type graduated to 0·1 deg. C. have been obtainable commercially, and with these, so far as the regulator is concerned, it should be possible to control within 10 millideg. Bare nichrome wire is used for the heating coils.

**Mr. L. B. Turner** (*in reply*): There are theoretical objections to the analogy between the passage of intermittent heat-pulses through the walls of the chamber and the passage of an electrical disturbance through a capacitance-inductance system. This is explained in my paper on the thermal hunting phenomena (*Proceedings of the Cambridge Philosophical Society*) referred to at the foot of page 402. Mr. Dixon does not make use of the analogy he suggests, but he is mistaken in thinking that I prefer the relay regime to the amplifier regime on

* "Thermostats for Medium Temperatures," *Actualités Scientifiques et Industrielles*, No. 276 (Hermann and Co., Paris, 1935).

the ground of higher hunting frequency. In the amplifier regime there is either no hunting or, if there is hunting, its frequency is practically the same as in the relay regime. I prefer the relay regime because of the superior sensitivity of the control of slave power by chamber temperature. This is explained in Section (4).

I welcome the further information of the behaviour of the Post Office thermostats, but I wish that Mr. Dixon had been able to give actual observations of inconstancy. Of one of the mains-operated ovens—it is not clear which—he writes: "In a test run of several days (similar to that recorded in the author's Fig. 21), no variation could be detected on a thermometer reading to 100 millideg." One would like to know what were the ambient temperature and voltage fluctuations during this test, and especially what were the actual fluctuations of the would-be constant temperature. A graph showing the observed fluctuations is so much more informative than a statement that, as far as could be observed, there was no inconstancy. With regard to the hunting which occurred, Mr. Dixon gives two tables. They exhibit clearly the lack in this thermostat of that close thermal union between slave and master coils whose importance I have stressed, and which he provided (in perfection) in his "thermautostat." Thus the middle line (normal mains voltage) of the second table shows that the relay, after remaining on for 1·75 minutes, switched off in response to an electrical cry of distress to the effect that the temperature was too high by 8·5 millideg.; but the temperature nevertheless continued to rise a further 121·5 millideg., and the whole on-off cycle lasted 4 minutes.

Mr. Dixon does not accept my verdict against the ingenious device, adopted in his "thermautostat," of uniting (identifying) the slave and master coils. Despite the completeness of this solution of the problem of maintaining good thermal contact between these two elements, there are two serious objections to its adoption. These are stated on pages 408 and 409 of the paper. Unless it is found impossible sufficiently to moderate the amplitude and/or the period of the hunting without resort to this device—and my apparatus demonstrates that it is not—these objections are, in my judgment, overpowering. Mr. Dixon is mistaken when he says: "Thus he admits the control sensitivity may be made higher in the thermautostat than in any other device." He bases this remark on my expression $35K/l$ as determining the limiting control sensitivity for no hunting. I agree that this quantity becomes infinite in the thermautostat, where $l$ is zero; but the course which I have advocated in the paper, and which my apparatus illustrates, is not to avoid hunting but to contrive that the hunting shall be innocuous. Mr. Dixon's subsequent remarks about $N_2/N_1$ are irrelevant, for this is a figure of merit for a thermostat with reference to the mean temperature; it has no bearing on the separation or identification of the slave and master coils.

I am not sure whether I understand Mr. Bell's first point. I think he suggests it would be advantageous somehow to render the translator insensitive to any unbalanced quadrature component of p.d. across the bridge. The response of the translator "RAC," when fed as here with mains-frequency signals, does depend somewhat upon phase; but I have found that a residual p.d., although in quadrature with the phase giving best sensitivity, spoils the sharp definition of the relay threshold. Actually, however, there is no difficulty in balancing the bridge perfectly with respect to the fundamental (or any single) frequency. The condenser marked 1 010 $\mu\mu$F in Fig. 14 effects this.

Mr. Bell is, of course, right when he points out that the same control sensitivity can be got with less power in, and therefore less excess temperature of, the master coil, if the sensitivity of the amplifier is increased. The practical difficulties of getting great sensitivity for mains-frequency signals in a mains-fed amplifier are, however, by no means trivial. My voltage amplification from the bridge diagonal to the input terminals of the translator is about 10 000; and I think that if I had gone much farther I should probably have fared worse. In fact, I did not attempt a second stage in the amplifier.

With regard to the relation between volume of chamber and heating power, the cubic relation is given thus. Let all linear dimensions be multiplied by 10 (and so the volume of the chamber by 1 000), and let the internal and external temperatures be unaltered. Cooling surface is multiplied by 100, but thickness of thermal insulation (glass silk and so on) is multiplied by 10; consequently rate of passage of heat is multiplied by 100/10.

I am glad to know that Mr. Gill, Mr. McPherson, and Mr. Willans, all think that the reduction of temperature inconstancy to such a small residue as is given by this apparatus may be of value for crystal and fork oscillators. At one time I supposed I had gone beyond the limit of interest to wireless engineers. But it should not be overlooked that extreme constancy may be of service in other fields; and further that the general design arrived at is equally applicable to chambers in which much larger inconstancy can be tolerated.

Mr. Mumford dislikes the idea of operating a thermostat with alternating current, because if the mains supply fails so does the thermostat. I would point out, however, that in most circumstances where the thermostat might be used much else would fail as well. Dependence on a.c. supplies is ever growing, and it would seem to be both necessary and practical to ensure that any intermission shall be of short duration.

I am glad that Mr. Willans adverts to means for adjustment of working temperature. In the present apparatus provision for some adjustment was added only as an afterthought, from motives which I think may be described as aesthetic. Any temperature over a range of 103 millideg. may be selected, the change being effected smoothly over a range of 23 millideg. by the scaled sliding (rotating) rheostat. (I may remark in passing that, without such facility, there would seem to be real experimental difficulty in determining the dependence on barometric pressure of any millideg. mercury thermometer.) There are three conditions which must be met if such an adjustment of working temperature is to be satisfactory. (*a*) The shunt resistors connected across a bridge arm for adjustment must have substantially the same temperature coefficient, and the same temperature, as the main bridge arms. (*b*) The contact resistances of plug and slider must be negligible. (*c*) The change of bridge ratio must not be so great that a readjustment of the compensator S, R (Fig. 11) is needed.

The smallness of the range of adjustment actually provided made it easy sufficiently to satisfy these conditions. But let us suppose that a range of $\pm$ 5 deg. C. were desired from the plug adjustment in the present apparatus. It would be necessary to shunt one of the bridge arms so that the resistance could be changed through $\pm$ 1·5 %. This could be done with an adjustable shunt resistor of lowest value not less than (say) 900 Ω. Condition (*a*) would be met by mingling the shunt resistor with the main resistors (A, B, Fig. 20) to ensure that no large temperature difference between them could occur. If both main and shunt resistors had a temperature coefficient of $10 \times 10^{-6}$ per deg. C. as contemplated on page 407, a discrepancy of 9 deg. C. between them would cause 1 millideg. change of working temperature. As regards condition (*b*), a switch or plug contact resistance in series with the 900 Ω would have to be as much as 0·08 Ω to cause 1 millideg. change of working temperature. Conditions (*a*) and (*b*) could, therefore, be met without difficulty. As regards condition (*c*), if the compensator S, R were correct at the middle temperature, I think that in Fig. 13, at the extreme settings of working temperature, the " With compensator " curve would be altered so as to make the ordinate intercepts between the two curves 1·5 % shorter than they are now. This would be hardly perceptible. It seems, therefore, that an adjustable range of at least $\pm$ 5 deg. C. could be provided in the present apparatus without appreciable detriment to its constancy.

Mr. Markwick refers to barometric pressure. No cause for any appreciable dependence on the barometer of the action of the thermostat was foreseen, but it was hoped that if such exists it would be exposed by systematic observations as in Figs. 21 and 21A. No relationship has been detected. He asks whether my thermometers could detect the hunting. The electrical thermometer used at The Institution was able to show a trace; but I certainly do not claim that either mercury or electric thermometers could be used to measure anything but the mean temperature of the chamber during several hunting cycles. The period of these fluctuations was about 1 sec., divided into equal durations of slave current on and off. Since the heating-up and cooling-down rate when the current is on and off is known with certainty as about 1 millideg. per sec. (being easily determined by observation of lengthy durations of on and off), it is certain that the master coil hunts through only about 0·5 millideg. above and below the temperature shown by the thermometer. The hunting amplitude at the inside surface of the chamber is, of course, less, viz. about $\frac{1}{7}$ millideg.

Mr. Markwick expresses surprise that I eschewed fluid stirring as a means of obtaining temperature uniformity, and enquires whether the temperature in the oven was uniform as well as constant. It is explained on pages 403 and 410 that the greatest temperature difference between any two spots on the aluminium cylinder in my actual apparatus is estimated as being well below 15 millideg.; and on page 403 it is suggested that this could easily be reduced to something very small indeed: I will guess 2 millideg. Without attempting calculations, I venture to question whether any even bulky and elaborate system of liquid convection, replacing the convenient metallic conduction of the actual apparatus, could achieve a better uniformity (supposing this were desired). If the master and slave coils were not embedded in the thick metal wall of the chamber, but in a mass of circulating fluid surrounding the chamber, it would, I think, be impracticable to contrive nearly such favourable spatial distribution of the coils over the chamber surface: and the less uniform this distribution, the more violent is the circulation required. In this connection it is interesting to note that, if 1 millideg. is an important interval, fluid turbulence may easily itself introduce non-uniformity. Water rises in temperature about $\frac{3}{4}$ millideg. for every foot of loss of head by turbulence. The water provided to distribute heat should be an object of suspicion as being itself a source of heat, unless the circulating pump requires no power to drive it!

# DISCUSSION ON
# "OPTIMUM SYMMETRICAL LIGHT DISTRIBUTIONS"*

**Mr. G. F. Freeman** (*communicated*): I have read Mr. McWhirter's paper with considerable interest, more particularly as it happens to bear on some work I had in hand at about the same time. In this I had obtained a contour curve, by a semi-empirical method, which gave a uniformity of 99 % for the square and 97 % for the triangular arrangements, which is rather better than that quoted by the author in his earlier paper and very little inferior to that now realized. For various reasons, however, I favour the contour depicted in Fig. A. It may be noted that this curve is symmetrical about its mid-point and that each half satisfies a simple power empiric

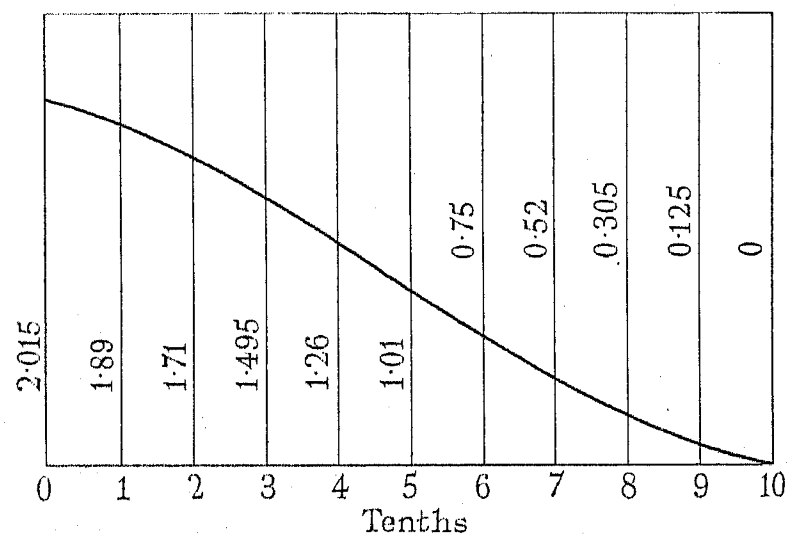



**Fig. A**

in which the exponent is 1·3. The figure should be compared with Figs. 1A and 2A of the author's paper, the total flux and cut-off being the same in each case.

Referring now to Fig. B, the full lines show the variation of maximum and minimum illumination with cut-off for this preferred curve, the cut-off being measured in terms of the space between adjacent sources along the side of the square, and the abscissae of the contour curve stretched or contracted to suit. The broken lines are re-plotted from the author's Fig. 10, except for points which have been added for cut-offs between 1·41 and 2. It is clear that at the expense of a slight lack of uniformity at high values of cut-off (i.e. with spacing closer than normal) a superior latitude is obtained in the other direction. For example, if a 2 : 1 ratio between maximum and minimum illumination is permitted, the fittings may be spaced some 20 % farther apart than fittings conforming to the author's contour, *for the same angular cut-off*. It is interesting to note a corresponding increase in the "dispersive angle." However, it is not suggested that this extreme spacing should always be used: rather should the fittings be disposed so that cut-off occurs at, say, 1·41 spaces; there will then be a superior depth of field above the ordinary working plane. Moreover, the slight lack of uniformity noted is quite unimportant in comparison with other factors of a practical nature, such as the asymmetry of individual lamp distributions (due to the form of the filament) and differences in lumen output between adjacent lamps. The percentage uniformity

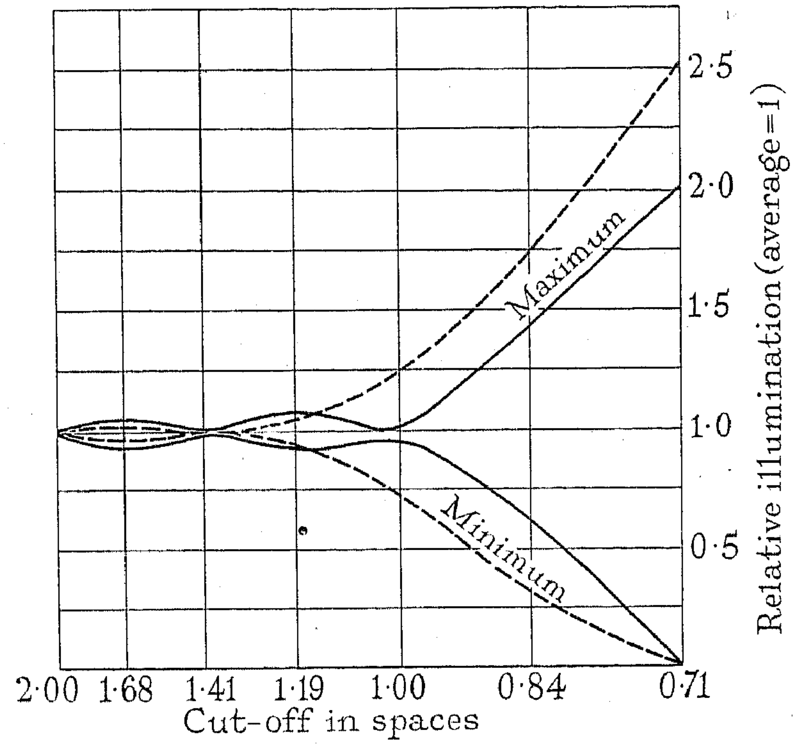



**Fig. B**

calculated for my curve for both square and triangular arrangements is set out in the Table for various cut-offs.

So far the argument has been purely hypothetical, with the object of arriving at the most favourable contour. It would be ungracious to deny the author the tribute he has rightly earned by his thoughtful study and great labour to this end. At the same time it must be conceded that from a practical point of view the chances of producing an economic reflector which will give precisely either his, or, for the matter of that, my contour do not seem particularly bright. From the design aspect, the most that can be done with an ordinary white vitreous-enamelled reflector, apart from controlling the cut-off and avoiding

**Table**

| Cut-off in spaces | | 1 | 1·19 | 1·41 | 1·68 | 2 |
|---|---|---|---|---|---|---|
| Uniformity, per cent | Square | 94 | 87 | 98 | 89 | 98 |
| | Tri'glr | 83 | 96 | 89 | 98 | 98 |

* Paper by Mr. H. R. S. McWhirter: *Journal I.E.E.*, 1937, vol. 80, p. 636.

excessive loss by multiple internal reflection, is to direct the specular reflection towards the appropriate quarter, leaving the unobstructed direct and diffusely reflected fluxes to their own devices. This, of course, is quite well known and usually results in an excess of flux just under the lamp, which will often be accentuated by a little peak of specular reflection right on the axis. This peak is particularly noticeable with vertical mercury-discharge lamps, due to the form of the light source, and the expedient of blocking the undesired emission can generally be ruled out as both clumsy and expensive. I do not think there is much to be gained by radical departure from the British Standard reflector for 1·5 heights' spacing, although on curve form alone the American R.L.M., judging by published data, would appear to offer some slight advantage. It may be noted in passing that all vitreous enamels are not identical either in the proportion of specular reflection or the smoothness or otherwise of the surface, and it is not always the most expensive enamel that is the most efficient or that gives the best distribution.

If I may conclude on a heretical note, why use polar curves at all? A distinction should be drawn between representations which have mainly a pictorial value and those which facilitate numerical interpolation, and in this latter respect the polar diagram, except where $dI/d\theta$ is small, is much inferior to a graph on ordinary Cartesian co-ordinates, using either a uniform angle scale or a sine scale (after Rousseau). An alternating voltage graphed on a circular base (except for purposes of harmonic analysis) would be regarded as a curiosity, and while I do not suggest that polar curves of light distribution are quite in the same category I venture to think that it is time they were superseded for technical purposes by something both more precise and more convenient, as indeed is already being done in certain isolated cases.

**Mr. H. R. S. McWhirter** (*in reply*): The comparison made in Mr. Freeman's Fig. B between his contour curve and mine is tantamount to comparing the light distributions derived from his contour curve with those derived from mine having the same angle of cut-off. Under such circumstances it is true that his light distributions would produce a greater uniformity ratio than mine at the higher values of spacing/height ratio. Mr. Freeman's light distributions would not do this, however, if they were compared with those of mine having the same dispersive angle. The conditions would then be reversed, as may be verified by superimposing on the curves in Fig. 10 in my paper similar curves derived from his Figs. A and B, in connection with which it may be mentioned that the ordinate 6·06 in Mr. Freeman's Fig. A corresponds to the dispersive angle.

I think that light distributions should be compared on the basis of the dispersive angle, for reasons which I have given in a previous paper,* and if this is done Mr. Freeman's light distributions appear inferior to mine. Mr. Freeman evidently produced them with the idea of meeting a particular requirement, viz. that the uniformity ratio should be as high as possible at high values of the spacing/height ratio for a given angle of cut-off. They are no doubt very suitable for this purpose, but it is a special one, and it is not to be expected that my light distributions should be the most suitable for all such special requirements that may arise in practice.

Mr. Freeman's remarks concerning enamelled steel reflectors indicate such a detailed knowledge of these that I hesitate to add anything to them. Judging from these remarks the common belief that it is difficult to control the light distribution with these reflectors seems to be well founded. However, it is well known that they have other advantages which justify their use in many cases.

With regard to the question of whether polar curves are the best means of representing light distributions, I think the point should be investigated but I have not so far reached any conclusion on the subject. One disadvantage of polar curves—that they convey no idea of the quantity of luminous flux involved—would be removed if the circle representing mean spherical candle-power were superimposed on each, as I have suggested in a previous paper.*

* *Journal I.E.E.*, 1936, vol. 78, p. 699.

### COUNCIL FOR THE YEAR 1937-1938

Owing to a clerical error the names of the vice-presidents for the year 1937-1938 were incorrectly set out on page 288 of "Institution Notes" in the last issue of the *Journal* (No. 488, August). The four vice-presidents for the 12 months commencing 1st October next are Sir Noel Ashbridge, B.Sc.(Eng.), Mr. J. R. Beard, M.Sc., Dr. A. P. M. Fleming, C.B.E., and Mr. Johnstone Wright.

### CONVERSAZIONE OF OVERSEAS MEMBERS

A Conversazione of members from overseas and their ladies was held in the Institution building on Wednesday evening, 7th July, the attendance being about 130. The proceedings commenced with a reception by the President (Mr. H. T. Young) supported by the Council. This was followed by a short address in the lecture theatre by Dr. P. Dunsheath, O.B.E., M.A., on " The Electron at Work and Play." Talking films of Sir Oliver Lodge, D.Sc., F.R.S., and Colonel R. E. B. Crompton, C.B., F.R.S., were also exhibited. A reunion then took place in the library.

The following members temporarily in England from overseas were present: Mr. J. R. T. Angier (Spain), Mr. R. Beck (Hungary), Mr. E. E. Benham (South Africa), Mr. V. H. Bray (Persia), Mr. B. F. Browne (Brazil), Mr. H. S. Bulley (India), Mr. C. W. Casse (India), Mr. C. Cater (Brazil), Mr. S. P. Chakravarti (India), Mr. H. E. Crowcroft (China), Mr. M. Dunlop (India), Mr. J. H. Eades (Burma), Mr. H. G. Hitchcock (New Zealand), Mr. F. G. Hogg (New Zealand), Mr. F. G. Hyland (India), Mr. P. S. Jackson (India), Mr. J. S. Jenkins (Straits Settlements), Mr. S. F. Kos (South Africa), Mr. D. H. Macnee (Australia), Mr. R. H. Martin (India), Mr. A. S. Mohan (India), Mr. R. P. Morris (China), Mr. A. J. Percival (China), Mr. J. O. Renaut (New Zealand), Mr. A. J. Smith (New Zealand), Mr. R. V. Talbot-Jones (South Africa), Mr. W. E. Tremain (Argentina), Mr. W. J. Trusler (India), Mr. P. L. Verma (India), Mr. R. J. Webb (Spain), and Mr. L. B. Whittaker (Jamaica).

### INDUSTRIAL DEVELOPMENT IN THE SPECIAL AREAS

The following is a copy of a letter which the President of The Institution received from the Commissioner for the Special Areas (England and Wales) and of the reply which has been sent by the Secretary:—

Commissioner for the Special Areas
(England and Wales),
Broadway Buildings, London, S.W.1.
7th May, 1937.

The President,
The Institution of Electrical Engineers,

Dear Sir,

It has been suggested to me that your members might be in a position to give very valuable assistance in the matter of attracting attention to the possibilities for industrial development in the Special Areas. They are, I am told, always called in at a very early stage in connection with proposals for the creation of new works being erected and might, thus, have opportunities of directing the attention of industrialists to the advantages of these Areas, from certain points of view, as compared with those which have been in the last few years more popular.

I am by no means convinced that the reasons actuating those who neglect the consideration of sites in the Special Areas are, on examination, as valid as at first sight they may appear. For instance, the opinion has been expressed that sites for new factories are often chosen merely because of the apparent advantage accruing from comparative nearness to certain parts of the market. It seems possible that this consideration takes insufficient account of the great improvements in transport facilities within recent years which have in effect brought the various parts of the country very much nearer to one another. From this point of view there is really no part of this country which can be considered remote from markets. Further, in many cases the markets for manufactured goods are spread over the whole country and, in the case of those which have markets abroad, nearness of the place of manufacture to the seaboard is of substantial importance. In this latter respect the Special Areas have marked advantages.

There are two other important factors in which the Special Areas present attractions not possessed by many other parts of the country and these are cheap fuel and large supplies of labour. In many of the districts in which industrial development has been most rapid recently, there has been appreciable and increasing difficulty in obtaining labour. Though this difficulty has, to some extent, been met by transference of people from the Special Areas, this is a process which has limitations which are likely to become more important in future.

In general, therefore, I feel convinced that the Special Areas have industrial facilities at least as great as any which can be presented by, for example, the South-Eastern Counties; and in certain other respects they have much greater advantages, such as their nearness to supplies of cheap fuel for power and to good seaports for the export trade.

The matter seems to me to be of such national importance that I am taking steps to impress these considerations upon industrialists at every available opportunity and I am convinced that the co-operation of members of your profession with their independent contacts throughout the industrial community would materially assist me in this direction. One way in which they could assist would be by giving talks or reading papers on the Special Areas and their connection with the work of the members of The Institution. Of course, my office

would, in the event of this suggestion being adopted, be pleased to provide any special information about the Areas which might be required.

I should be greatly obliged if you would think the matter over and let me know whether you consider that there is any way in which members of your Institution can, consistently with their professional obligations, co-operate in this matter. If so, I should be glad to arrange for one of my Industrial Officers (who have been specially appointed to maintain contact with industry on this question) to wait upon any representative you would care to name.

Yours very truly,
(Signed) Geo. M. Gillett.

The Institution of Electrical Engineers,
Savoy Place, London, W.C.2.
2nd July, 1937.

The Commissioner for the Special Areas
(England and Wales),

Dear Sir,

Your letter of the 7th May addressed to the President has now been before the Council, who have given it most sympathetic consideration. They are willing to arrange to display in the Library any literature which you may be able to supply relating to the possibilities for industrial development in the Special Areas, and they also think that it might be possible to assist you by giving facilities for a lecture to be delivered before our members. The Institution will be prepared to make the necessary arrangements for this lecture and to discuss with you the manner in which it should be presented.

The Council regret very much indeed that, having regard to the terms of its Charter, it is not possible for The Institution to assist your department in a more practical way, but there are several industrial and commercial bodies in existence materially concerned with electrical engineering matters, and the Council would gladly furnish you with information regarding these bodies.

I am to add that, if you concur, the Council would have your letter published in the Institution *Journal*, together with my present letter, and the position would thus be brought to the notice of all members of The Institution.

Yours faithfully,
(Signed) P. F. Rowell,
*Secretary*.

## DISCUSSION ON LUBRICATION AND LUBRICANTS

The Council of The Institution of Mechanical Engineers, with the co-operation of other societies and institutions, have decided to hold a General Discussion on Lubrication and Lubricants from Wednesday afternoon, 13th October, to Friday morning, 15th October, when a series of about 140 papers from leading authorities throughout the world will be presented.

The papers will be grouped under the following four headings: (1) journal and thrust bearings; (2) engine lubrication; (3) industrial applications; (4) properties and testing. Advance copies of the papers will be available for use at the meetings, and the complete proceedings will be issued as a bound volume. The prices of the bound volume and the advance copies are as follows:—

Complete set of advance copies and bound volume of Proceedings at the special reduced rate of £1, if ordered before 28th September, 1937.

Bound volume of Proceedings, if not ordered before 28th September, 1937, at £1 5s.

Complete set of advance copies at 8s.

Advance copies of the papers at 2s. 6d. per group.

An Exhibition will be held at the Science Museum, South Kensington, from the 13th to the 26th October to illustrate the subjects under discussion, and will be devoted to lubricants, bearings, and bearing materials, as well as to testing and other apparatus.

Application forms for tickets of admission to the Discussion and for copies of papers, together with any further information, may be obtained from the Secretary, The Institution of Mechanical Engineers, Storey's Gate, St. James's Park, London, S.W.1.

## OVERSEAS ACTIVITIES

### Australia

**Queensland.**

At a meeting held on the 22nd April, 1936, Mr. J. S. Just, Chairman of the Local Committee, in the chair, a paper by Mr. J. E. Morwood, Associate Member, entitled "High-Tension Metalclad Switch and Control Gear, with special reference to the New Switchhouse at New Farm Power House," was read and discussed.

On the 17th July, 1936, was held a Joint Meeting of local members of the I.E.E. and of the Institution of Engineers, Australia. Mr. J. S. Just, Member, and Mr. A. E. Axon, Associate Member, jointly presided, and the following papers on "Urban Transport" were read: "Electric Traction for Cities and Suburbs," by Mr. W. Arundell, Member; "Diesel Engines as Applied to Transport," by Mr. H. S. Dean, B.E. In addition, short papers on various means of traffic control (by Mr. E. B. Freeman, Associate Member), and the functions and capabilities of urban railways (by Mr. A. E. Tuffley) were read.

Messrs. N. J. Amos, W. E. Bush, D. J. Garland, A. S. Deacon, L. G. Pardoe, W. Nicoll, and G. L'Estrange, also Dr. A. Boyd and Mr. J. S. Just, took part in the ensuing discussion.

A vote of thanks to the authors was carried with acclamation.

The annual social function was held on the 25th September, 1936, at the Belle Vue Hotel, Brisbane. The Chairman of the Local Committee, Mr. J. S. Just, and Mrs. Just, were host and hostess. Among those present were a number of representatives of technical bodies.

At a meeting held on the 23rd October, 1936, in the Lecture Hall of the Engineering School, University of Queensland, Mr. J. S. Just in the chair, a demonstration of the cathode-ray oscillograph was given by Mr. R. P. Goodman, a student of the University, assisted by Mr. McCorkell, a fellow-student. In the discussion which followed, the following members took part: Messrs. L. G. Pardoe, R. H. Clarke, W. I. Monkhouse, W. Arundell, and J. S. Just.

**South Australia.**

The Biennial Dinner was held at the Oriental Hotel, Adelaide, on the 26th August, 1936, and was presided over by Mr. F. W. H. Wheadon, Chairman of the Local Committee. During the course of the evening a résumé of the paper by Dr. Russell Reynolds, Member, on "Cineradiography" (see vol. 79, page 389), was given by Mr. E. V. Clark, Associate Member. This was followed by a paper by Mr. J. C. Stobie, Associate Member, on "Analysis of the Adelaide Electric Supply Company's Daily Load Curve, and the Proposal to introduce Reactive Condenser Equipment." The paper was read by Mr. J. R. Brookman, Member, in Mr. Stobie's absence on account of illness. Nineteen members and guests attended, and a general discussion took place on both the papers.

**Victoria and Tasmania.**

The Annual Dinner was held on the 27th April, 1936. During the course of the evening Mr. H. R. Harper, Chairman and Honorary Secretary of the Local Committee, gave a short address, illustrated by lantern slides, on matters of interest in connection with his recent trip abroad, and particularly in regard to his visit to the headquarters of The Institution in London.

On the 4th August, 1936, there was a joint conversazione with the Electrical Engineering Branch of the Institution of Engineers, Australia. During the evening Mr. Harper repeated the address which he had delivered at the Annual Dinner.

## Ceylon

At a meeting arranged by the Local Committee and held at Colombo on the 15th May, 1936, the paper by Mr. A. L. Lunn, Member, entitled "The Equipment and Performance of Steel-Tank Rectifier Substations operating on the Underground Railways of the London Passenger Transport Board" (see vol. 78, page 123), was read by Mr. C. H. Jones, Associate Member, and was discussed.

At a meeting held on the 25th September, 1936, Mr. G. E. Misso, Associate Member, opened a discussion on "The I.E.E. Wiring Regulations, with special reference to Section 4 (The Installing of Conductors and Cables), and Section 10 (Earthing)." Several members took part in the discussion.

At a meeting held at Colombo on the 5th February, 1937, Major C. H. Brazel, M.C., in the chair, a paper by Messrs. C. H. J. de Mel and T. S. V. Tillekeratne, Graduates, entitled "Hydro-electric and E.H.T. Developments in India," was read by Mr. D. P. Bennett, Graduate, and was discussed.

The third Annual General Meeting of The Institution members in Ceylon was held in Colombo on the 9th April, 1937, Major Brazel in the chair. Prior to this a visit had been paid to the works of Messrs. Walker, Sons, and Co. The party was conducted by Messrs. Starbuck and Bennett, to whom a vote of thanks was passed by the Chairman. The Annual Dinner, at which the Chairman delivered an Address, was held after the Annual General Meeting.

## China

A joint garden party, in which the China Centre of the I.E.E., the Chinese Institute of Engineers, the Chinese Institute of Electrical Engineers, the Engineering Society of China, the Shanghai Association of the Institution of Civil Engineers, and the China Branch of the Institution of Mechanical Engineers, took part, was held on the 10th October, 1936, in the grounds of St. John's University, Shanghai, and was attended by some 400 members and guests.

At a meeting of the China Centre held at Shanghai on the 9th November, 1936, in conjunction with the Engineering Society of China and the Shanghai Branch of the Institution of Civil Engineers, Mr. A. J. Percival in the chair, a paper by Lieut.-Commander H. T. Powell, R.N., Associate Member, entitled "Electrical Equipment in Warships," was read and discussed, Messrs. Wilson, Clarke, Flemons, Rogers, Welch, and Emmes, taking part in the discussion. A vote of thanks to the author, proposed by the Chairman, was carried with acclamation. The meeting was attended by 78 members and guests.

A joint meeting of the China Centre, the Engineering Society of China, the Shanghai Branch of the Institution of Civil Engineers, and the China Branch of the Institution of Mechanical Engineers, was held in Shanghai on the 18th January, 1937. Mr. C. R. Webb, Chairman of the Local Centre, was in the chair and 61 members and guests were present. A paper by Mr. N. L. Anderson, Associate Member, entitled "Notes on Modern Distribution Practices," was read and discussed. Messrs. Crofton, Chow, Hunter, Knox, Mellor, Turner, Webb, and Wilson, took part in the discussion. A vote of thanks to the author, proposed by the Chairman, was carried with acclamation.

Another meeting of the same bodies, presided over by Mr. J. Haynes Wilson, M.C., was held on the 8th February, 1937. Thirty-five members and guests were present. A paper by Mr. C. W. Yung, entitled "The Manufacture of Electrical Equipment in China," was read and was discussed by Messrs. Miles, Fong, Flemons, Moore, Emmes, and Wilson. A vote of thanks to the author was proposed by the Chairman and was carried with acclamation.

A further joint meeting of the China Centre, the Engineering Society of China, and associated Institutions, took place on the 1st March, 1937, Mr. C. R. Webb being in the chair and 60 members and guests being present. A paper by Mr. J. A. McKinney, Associate Member, entitled "Remarks on the Application of Electricity to Industrial Power and Heat, with special reference to Shanghai," was read. Messrs. W. A. Ankerson, N. W. B. Clarke, J. Frost, A. J. Percival, S. P. Simpson, and C. R. Webb, took part in the ensuing discussion. A vote of thanks to the author, proposed by the Chairman, was carried with acclamation.

On the 16th March, 1937, a further meeting of the same bodies took place under the chairmanship of Mr. C. R. Webb, 29 members and guests being present. A paper by Mr. L. G. Freeth, Associate Member, entitled "Modern Long-distance Telephony," was read and discussed. Messrs. N. W. B. Clarke, S. Flemons, H. Graham, L. B. Harmer, and J. T. Rogers, took part in the

discussion, at the conclusion of which the Chairman moved a vote of thanks to the author, which was carried with acclamation.

A dance, which was attended by 135 persons and which proved very successful, was held at the International Club on the 20th March, 1937, Mr. W. Miles having charge of the arrangements.

The Annual General Meeting was held on the 24th May, 1937.

In addition to the papers mentioned above, the following was read during the period under review (1936–37): "The Development of Electrical Power in Nanking," by Mr. M. H. Pai.

## India

**Bombay.**

At a meeting held on the 27th October, 1936, the Chairman of the Local Committee, Mr. R. G. Higham, delivered his Inaugural Address on "Electrical Accidents." This was followed by a discussion. The meeting was attended by 45 members.

On the 26th January, 1937, a paper on "Air Conditioning" was read by Mr. E. D. Wilson, 68 members and guests being present.

At a meeting held on the 23rd February, 1937, a paper entitled "Electrical Developments in the City of Bombay and its Suburbs" was read by Mr. R. D. Mistry, Associate, before an audience of 29 members and guests.

The following visits took place during the year:—

| | |
|---|---|
| 6th July. | Works of the Hewittic Electric Co., where a cinematograph film illustrating the manufacture of glass-bulb rectifiers was shown to an audience of 75 members and guests. |
| 11th July. | Kalyan power house of the G.I.P. Railway. Thirty-eight members were present. |
| 12th Sept. | Bassein Road mercury-arc rectifier substation of the B.B. and C.I. Railway. Thirty-one members were present. |
| 21st Nov. | Beam wireless station at Kirkee, where lunch was provided for the visitors, who numbered 24, by Sir Rahimtoola M. Chinoy. |

**Calcutta.**

A discussion on "Water-Tube Boilers and their Manufacture" took place at a meeting arranged by the Local Committee and held on the 29th April, 1936, and an invitation to attend the meeting was issued to the local members of the Institution of Engineers (India). The discussion was opened by Mr. A. W. Pedder, B.Sc., who exhibited a cinematograph film. Thirty-four I.E.E. members and guests were present. On the 19th June, 1936, there was a further meeting, attended by 53 members and guests, at which Mr. C. Penn Hughes opened a discussion on "Glass-bulb Rectifiers," illustrating his remarks by a film.

A further meeting was held on the 8th December, 1936, at which Prof. F. W. Sharpley, F.R.S.E., Member, read a paper, illustrated by lantern slides, on "The Applications of Electricity to Coal Mining in India." Thirty-three members and guests were present.

On the 12th January, 1937, a further meeting was held at which Mr. R. G. Millard, Associate Member, read a paper, illustrated by lantern slides, on "Pulverized Fuel for Power Station Boilers." Thirty-three members were present, several of whom took part in the ensuing discussion.

A visit, in which 33 members took part as the guests of the Bengal Telephone Corporation, Ltd., was arranged to the Calcutta Telephone Exchange on the evening of the 9th February, 1937. Later in the evening a discussion was opened by Mr. F. G. Hyland, Associate, on "The Central-battery Telephone Exchange."

A further meeting took place on the 9th March, 1937, at which Mr. W. G. Cross, Associate, opened a discussion on "Modern Tramways." Thirty-six members and guests attended.

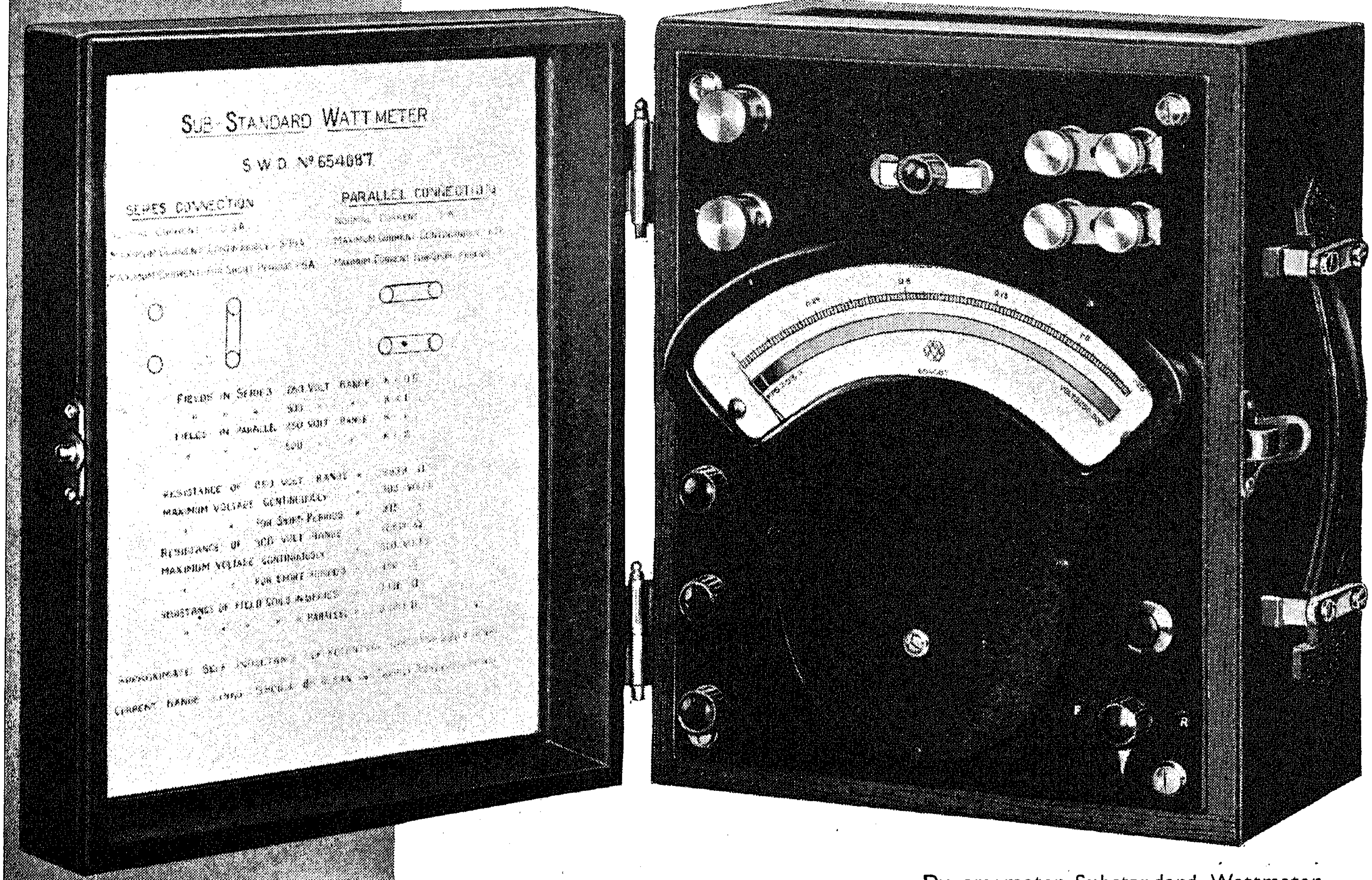
On the 9th April, 1937, Mr. W. E. Fleming, B.Sc., opened a discussion, illustrated by a film, on "The World's Largest Transformer." The meeting was attended by 29 members and guests.

**Lahore.**

At a meeting held on the 10th December, 1936, Prof. T. H. Matthewman, Chairman of the Local Committee, in the chair, a paper by Mr. S. P. Ganguly, Associate Member, entitled "An Analysis of the Working of Power Stations in the Punjab," was read and discussed. Among those who took part in the discussion were Messrs. N. B. MacMillan, P. N. Mukerji, T. S. Rao, and N. Thornton.

# ELECTRICITY SUPPLY (METERS) ACT, 1936

AND THE RECENTLY ISSUED MEMORANDUM CONCERNING APPROVED APPARATUS FOR METER TESTING

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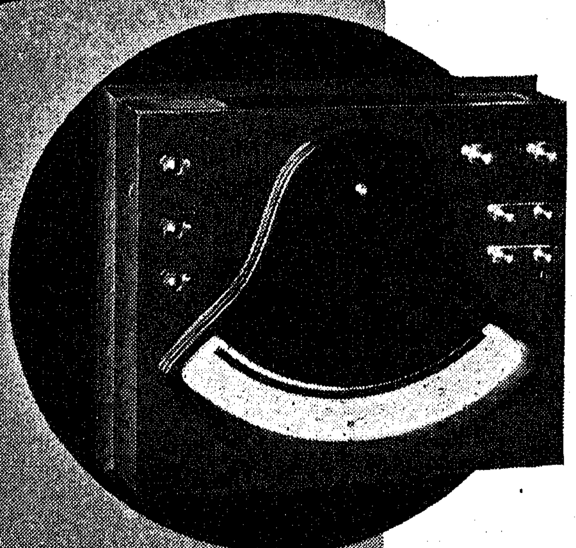

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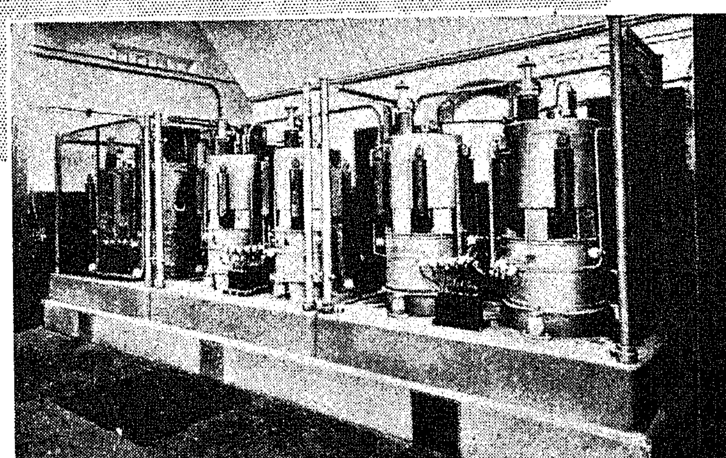

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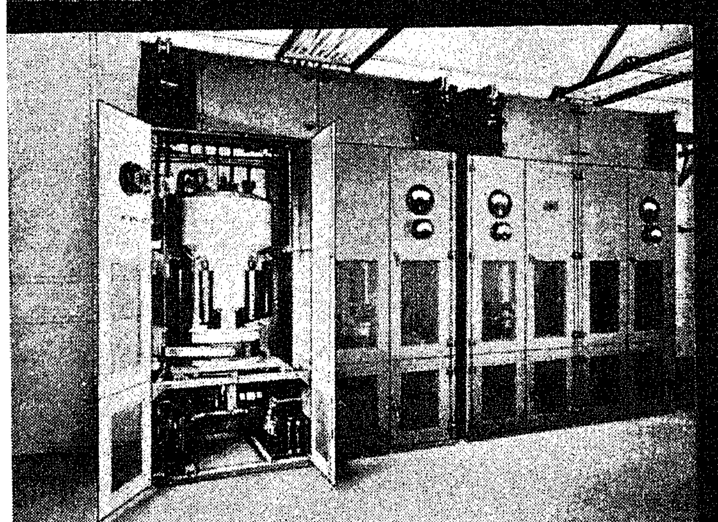
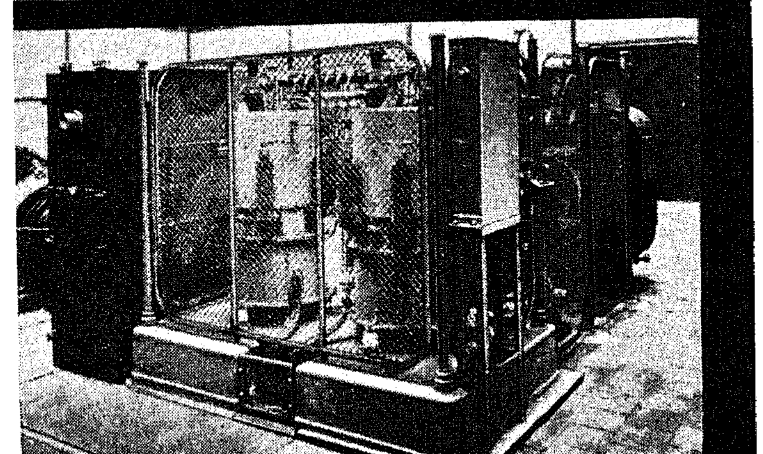


## MUNICIPAL • SERVICE

Four 250 kW units in the Percy Road sub-station of Finchley Borough Council.



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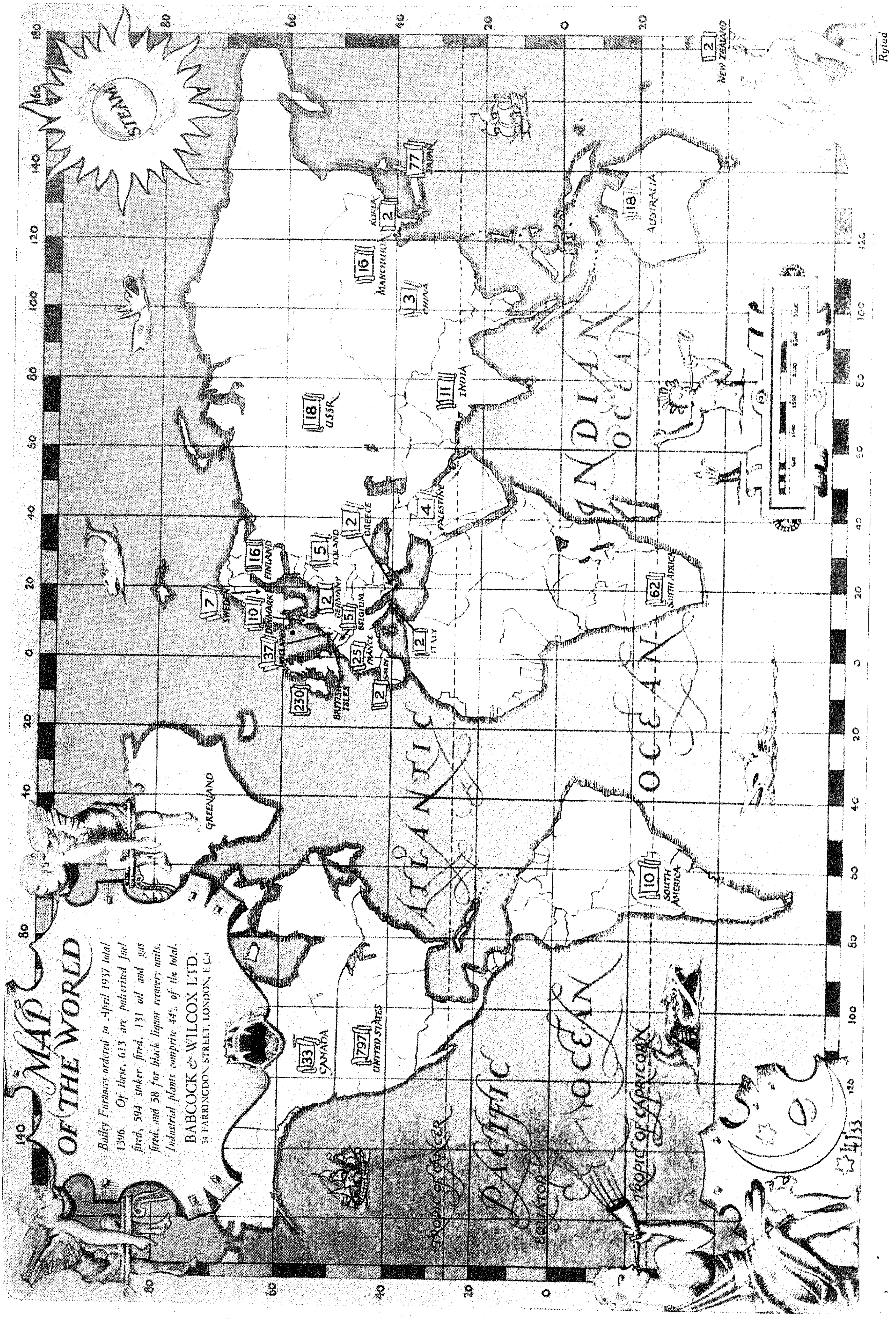
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4 PALESTINE
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18 U.S.S.R.
11 INDIA
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77 JAPAN
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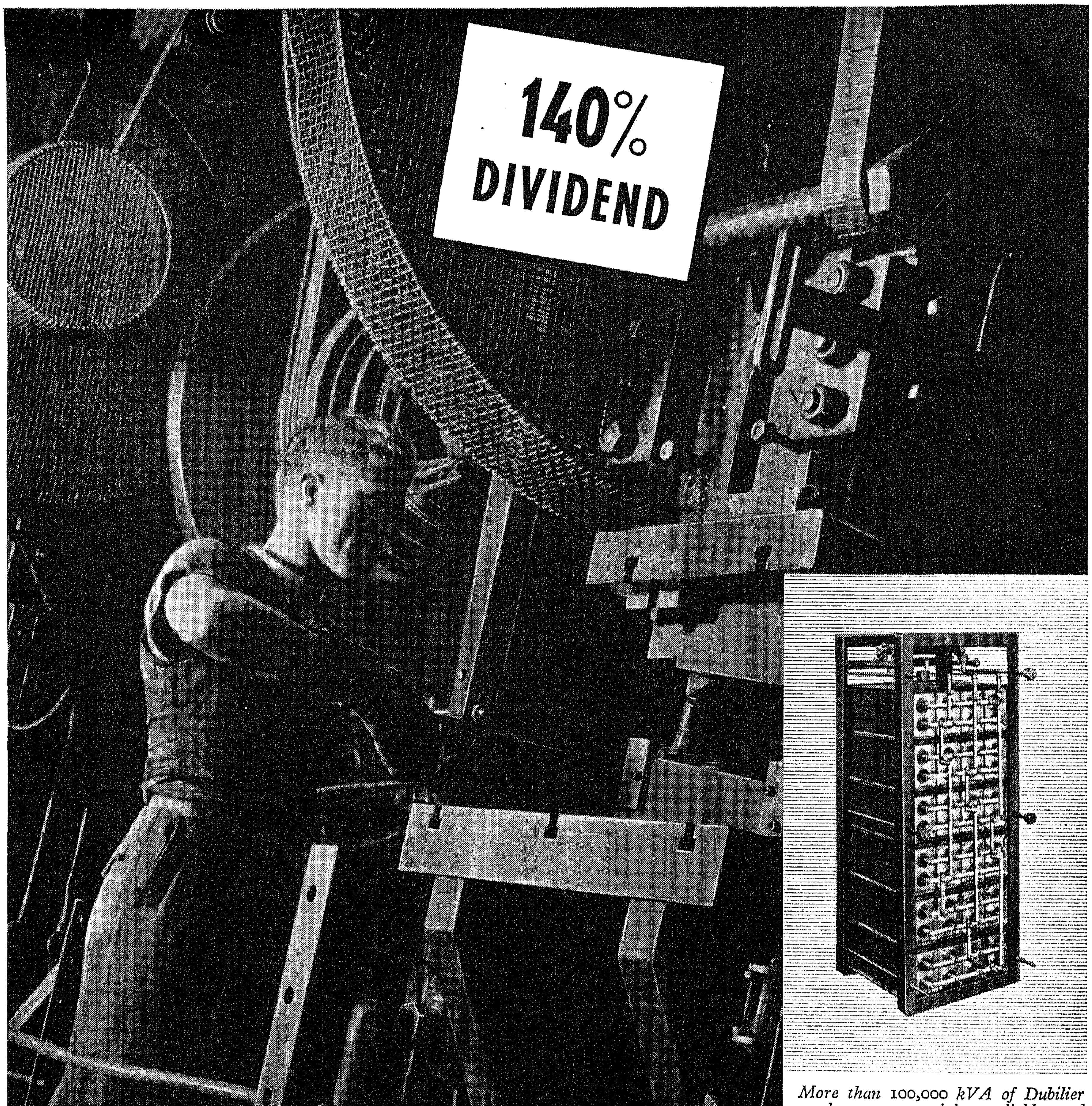


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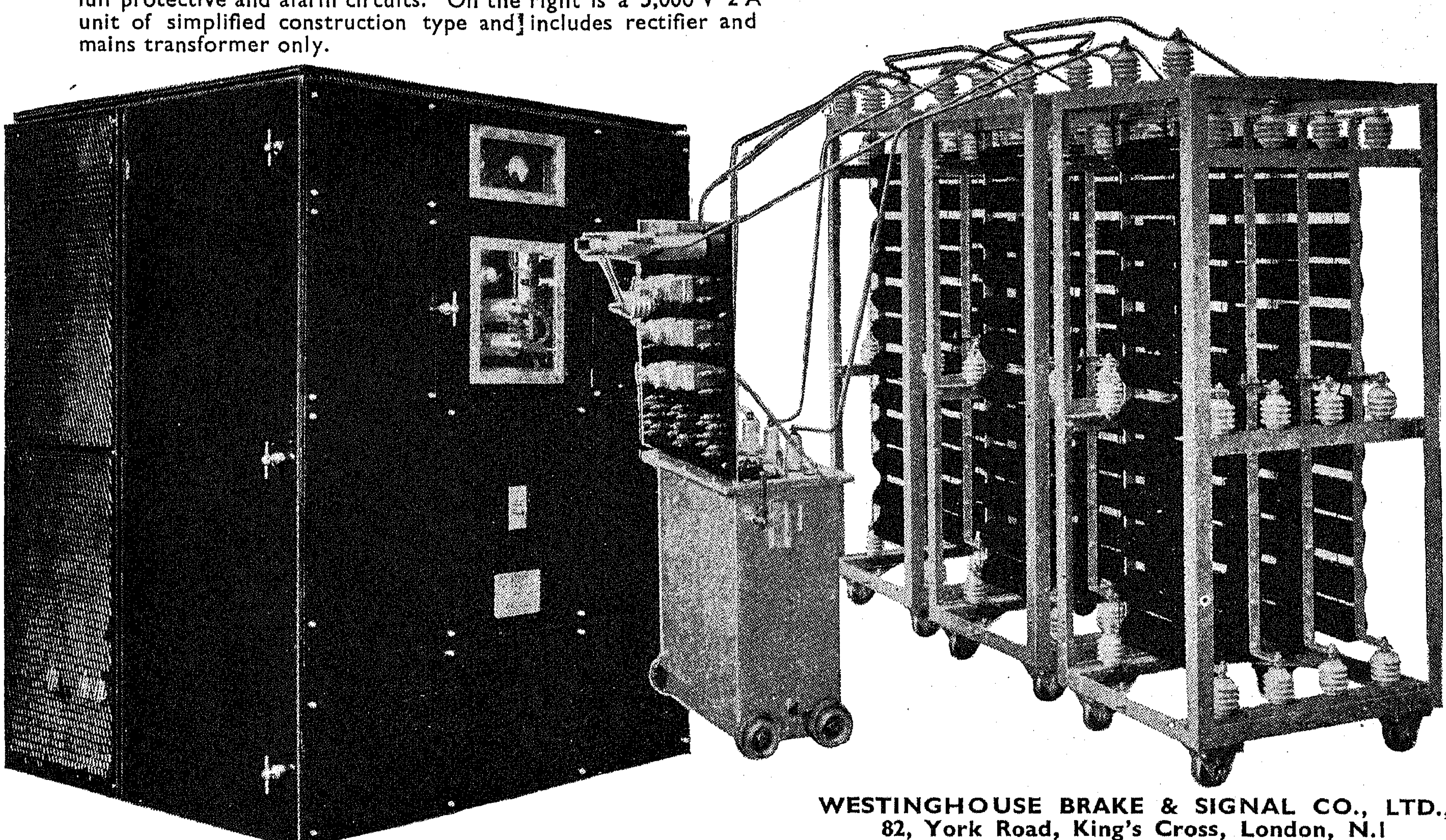

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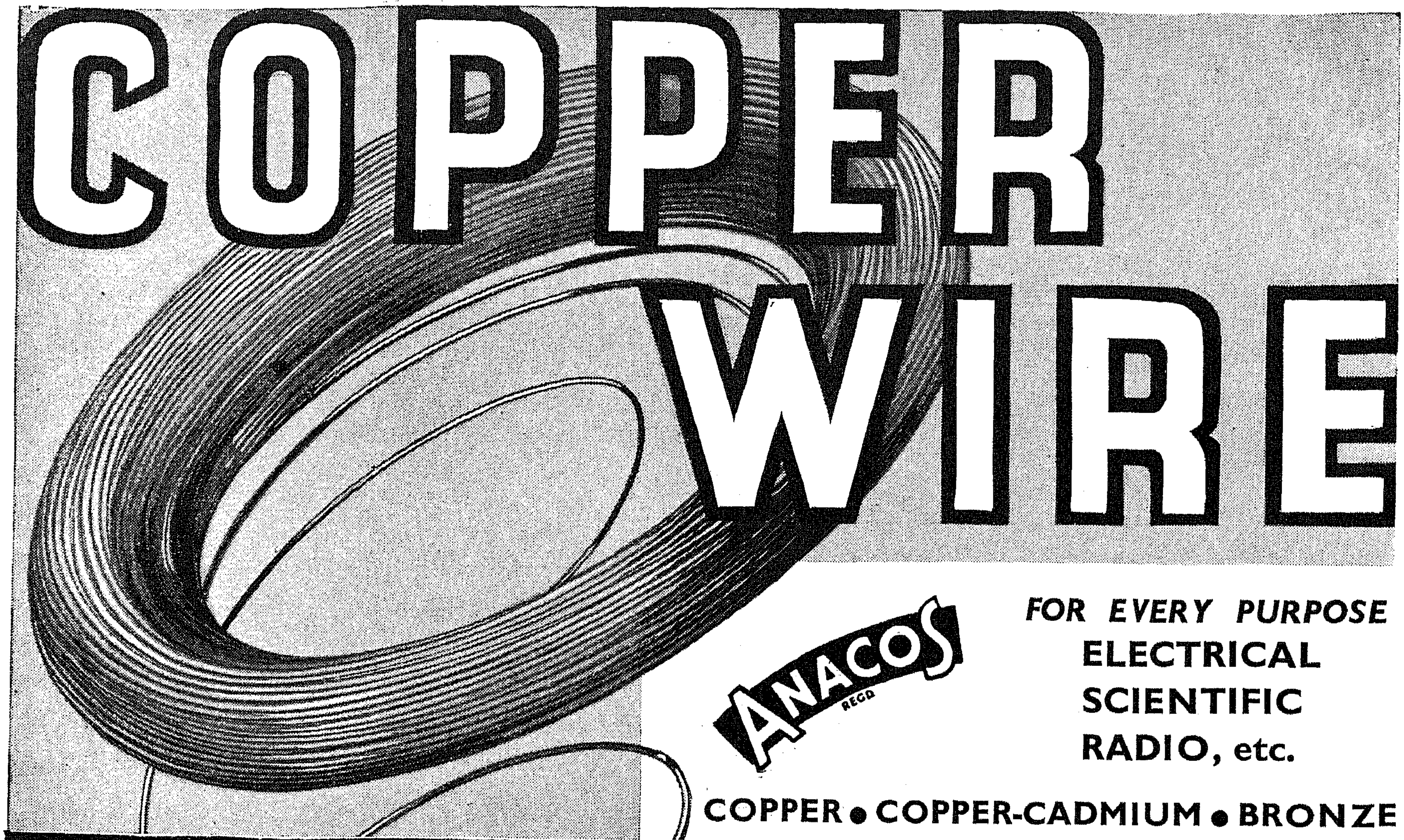


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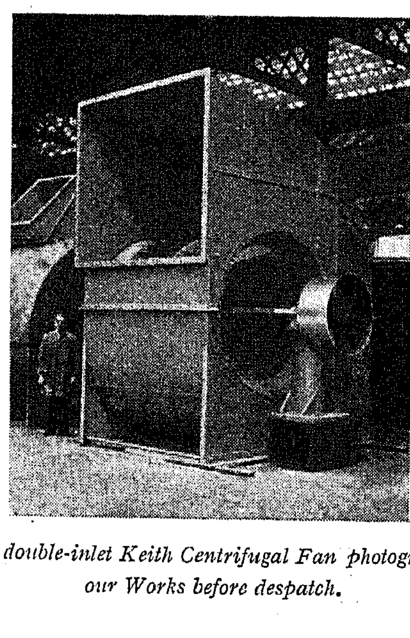

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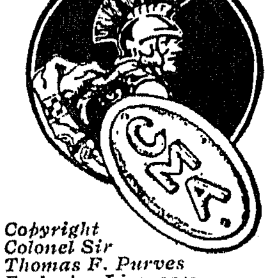


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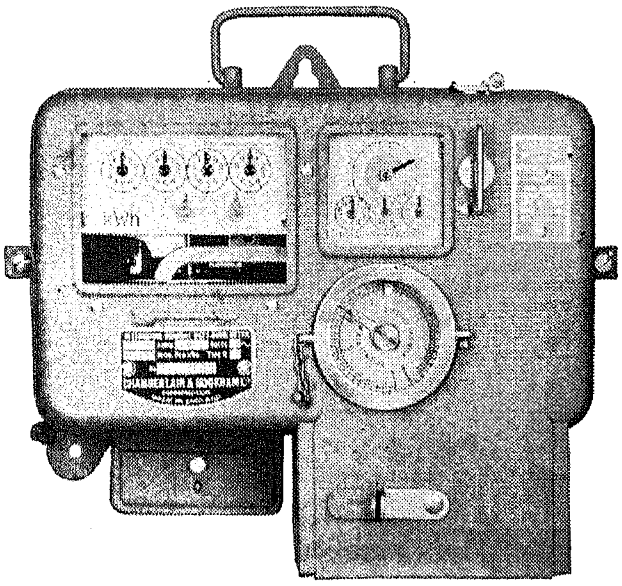

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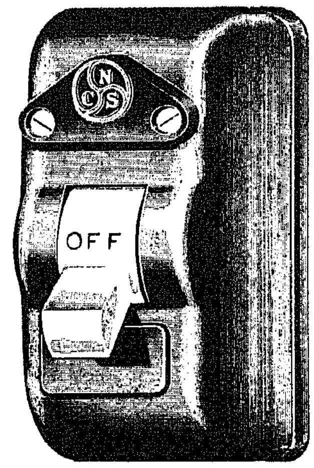

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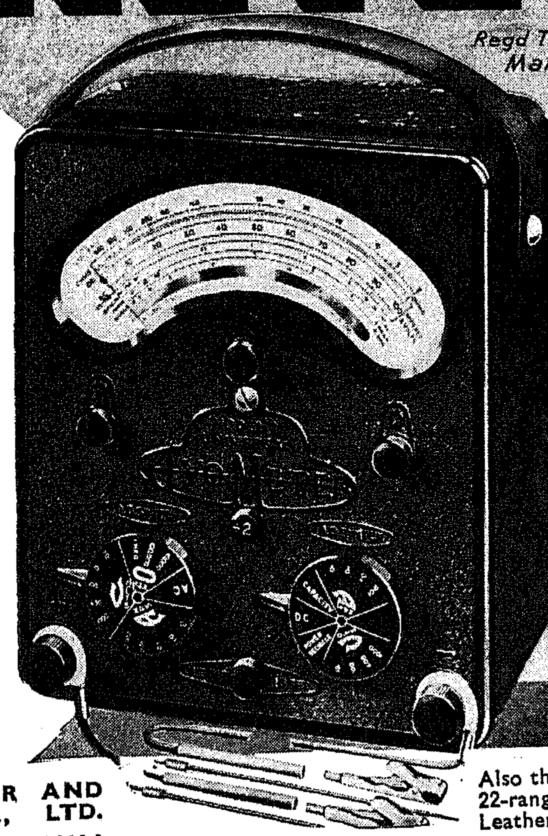

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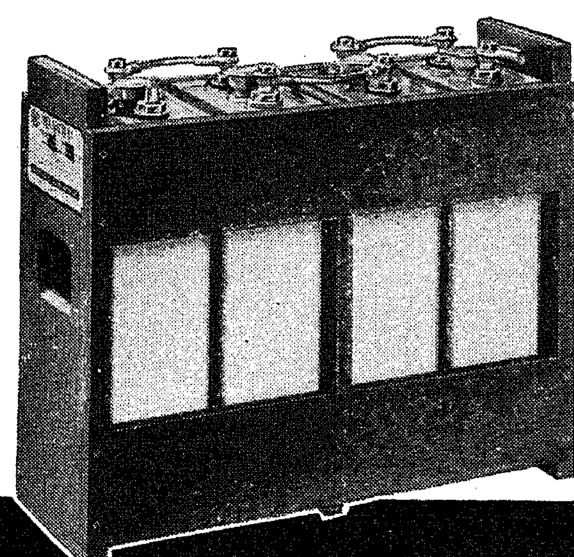

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